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Technical Literature Review

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War-time Rubber Exploitation in Tropical America

From April, 1942, through August, 1944, when the world's great source of rubber in Malaya and adjacent areas was not available, the United States obtained 32% of its needs from tropical American countries, 15% from Liberia and the remainder from Ceylon, India and African sources other than Liberia.

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History

The capture of the world's leading rubber-plantation areas, those of southeastern Asia and adjacent islands, by the Japanese in early 1942 closed 90% of the world's rubber supply to the Allied Powers. As a result of the rubber famine thus induced, the United States Government took immediate action to resuscitate the moribund Latin American sources of rubber which had languished for nearly a quarter of a century in the face of their inability to produce rubber as cheap as that from the Far East. The task of developing the Latin American rubber resources during World War II was assigned to the Reconstruction Finance Corporation, first through its subsidiary, the Rubber Reserve Company (prior to February, 1943), then to a new subsidiary, the Rubber Development Corporation, organized in February, 1943. The operations of these agencies in Latin American countries were conducted within the framework of contracts concluded between the United States Government and the governments of rubber-producing Latin American countries and the colonies of British Guiana and Trinidad.

These contracts had four principal objectives: *a*) to centralize rubber exploitation and to arrange a uniformity in production methods, whenever desirable, in the various countries; *b*) to fix prices paid for rubber and thus to prevent uncontrolled price inflation and private speculation; *c*) to furnish technical advisers and supplies required for rubber production to rubber-producing countries; *d*) to prevent Axis agents and sympathizers from securing rubber for their countries or from destroying rubber to prevent its reaching the Allied Powers.

The principal terms of these contracts, which were virtually the same for all countries involved, may be summarized thus:

1. The rubber-producing countries of Latin America agreed:

a) To sell all their exportable surplus of crude rubber to the United States for a fixed period;

b) to initiate an internal system of rationing and conservation of rubber and rubber products;

c) to waive customs duties on all imports of supplies by agents of the Rubber Development Corporation for purposes of rubber production;

d) to render all possible aid through local governmental agencies and officials to agents of the Rubber Development Corporation.

FIG. 1 (*Upper*). *Hevea brasiliensis* estate in British Guiana, after clearing of undergrowth.

FIG. 2 (*Lower*). "Opening" a large *Hevea* tree. Note half-spiral cut, vertical latex channel, spout and latex receptacle.

FIG. 3 (*Upper*). Leaves and flowers of *H. brasiliensis*.
FIG. 4 (*Lower*). Leaves and fruits of *H. brasiliensis*.

2. The United States government agreed, through its Rubber Development Corporation:

a) To pay a fixed scale of prices in all countries for various types and grades of rubber;

b) to guarantee to each country an annual supply of rubber and of rubber commodities, sufficient to satisfy minimum essential needs.

c) to furnish administrative officials and rubber technicians who would supervise rubber production, train nationals in rubber production and arrange for shipments of supplies into these countries and of crude rubber to the United States.

d) to furnish supplies directly related to rubber production (tapping knives, latex cups, coagulating acid, materials for constructing coagulating sheds and smokehouses, etc.) and supplies indirectly related to rubber production (machetes, lanterns, kerosene, fishhooks, outboard motors, vegetable seeds, atabrine and other drugs, etc.). In most areas these supplies were furnished at cost to local rubber producers and contractors, but under some circumstances they were given without charge to stimulate interest in rubber exploitation.

The uniformity of these contracts had a major advantage, namely, in causing the Latin American governments concerned to recognize that equal treatment was being accorded all rubber-producing countries in matters of payment, supplies, etc. At the same time, however, because of varying rates of exchange and of differing local costs, the fixed price schedule for rubber resulted in considerable variations in the profit margin for rubber producers in the several countries involved. Thus the contractual price scale made possible a reasonable profit for rubber producers in Brazil, Peru, Bolivia and certain other countries, but did not enable rubber producers in Venezuela to gain much profit. As a result, rubber production in Venezuela was prosecuted only with great difficulty, since tappers and contractors could earn more money in bleeding chicle, in cattle raising, in farming or in field work for American oil companies. In order to offset this disadvantage and to stimulate rubber production under such conditions, special inducements, such as bonus payments, provision of food supplies and remission of charges for tapping equipment, were made outside the contractual framework in certain areas.

The operations of the Rubber Development Corporation occasioned numerous criticisms during and immediately following the war. Certain of these criticisms were valid, for the Corporation was guilty of maladministration in some aspects of its work: in the occasional selection of officials ill-suited to and inadequately trained for their work, in duplication of effort, in the initiation of projects doomed from their inception to failure, in the procurement of inappropriate supplies and in the weaving of bureaucratic red tape which sometimes interfered with or delayed rubber exploitation. Some of these criticisms were unfair, however, in view of the haste with which the rubber-procurement program had to be initiated and prosecuted and of the many serious problems involved in the renascence of an industry which had lain dormant for nearly 25 years. An unbiased evaluation of the operations of the Rubber Development Corporation at this time would probably demonstrate that they were no more wasteful or inefficient than those of other war-born governmental agencies or of non-combat activities of the Army and Navy. The critical rubber shortage, fraught with grave danger to our security, demanded measures which could not reasonably be judged by efficiency experts on peacetime standards.

The problems involved in the reactivation of the tropical American rubber

industry were but little different from those which caused the industry to succumb a quarter of a century earlier as a result of competition from the rubber plantations of Malaya, Sumatra and Indo-China. Sparse populations in rubber areas, prevalence of malaria and other diseases, remoteness of rubber areas from the benefits of civilization, annoying and sometimes dangerous animal pests, such as snakes, scorpions and stinging and biting insects, widespread distribution of the leaf-blight disease of *Hevea*, difficulties in recruiting tappers to enter distant and comfortless rubber regions, lack of housing, inadequacy of food supplies and medical services, almost non-existent transportation facilities in vast regions and the presence of numerous rapids in many large rivers constituted obstacles which challenged the best efforts of administrators and field specialists and which demanded extreme and often expensive measures for their conquest. That the industry was revived with fair success in the face of these obstacles and that the revival aided materially in the prosecution of the war are indicated by the increase in tropical American rubber production from about 10,000 tons in 1941 to nearly 40,000 tons in the year ending August, 1944. Of the total amount of crude rubber acquired by the United States from all foreign sources from April, 1942, through August, 1944, 32% was produced by tropical American countries, about 15% by Liberia and the remainder chiefly by plantations in Ceylon, India and African sources other than Liberia. The average cost of rubber production in tropical America during this period was 68.02 cents per pound, as contrasted with 28.74 cents per pound for rubber from India and Ceylon and 27.79 cents per pound for Liberian rubber. Although this disparity in production costs appears great, it becomes understandable when one considers that all the rubber from India, Ceylon and Liberia was produced by plantation trees growing on estates which had been in operation for a number of years prior to the war and that most of the rubber from tropical America was harvested from wild trees growing in remote forest areas and from plantations which had been abandoned for nearly 25 years.

The Rubber Development Corporation employed only limited numbers of nationals in the countries in which it functioned. These were principally office workers, shipping agents, field demonstrators and technicians trained by American field men, liaison officials to work with local governments, and a limited number of mechanics to maintain RDC launches, motors and other mechanical equipment. RDC did not ordinarily employ tappers and other field laborers; these workers were in the employ of private contractors or business firms or of agricultural and other agencies of the several Latin American governments. Officials of RDC did participate, however, in labor relations in an indirect capacity, for example, in aiding in transporting laborers to rubber-producing areas, in furnishing laborers with food bonuses, vegetable seeds and drugs, and in mediating disputes between tappers and their local employers in matters of wages, sizes of tapping " tasks " and other working conditions.

Rubber-Producing Species of Tropical America

So serious was the war-time rubber shortage in the United States that almost every rubber-producing species in tropical America was exploited or was tested for rubber possibilities. In some instances promising rubber-producing species were not extensively tapped because of insurmountable obstacles to their exploitation; inaccessibility, impossibility of recruiting tappers for the regions in

FIG. 5 (*Upper*). Single half-spiral tapping on *H. brasiliensis* after one year of tapping.
FIG. 6 (*Lower*). Double half-spiral tapping panel on *H. brasiliensis*.

FIG. 7 (*Upper*). Badly tapped panel, showing exposure of wood among bark islands. Marginal growth from such islands will regenerate bark over exposed wood.

FIG. 8 (*Lower*). Badly tapped panel, showing almost complete removal of bark. Regeneration over such an exposed area is impossible.

FIG. 9. Straining diluted latex of *H. brasiliensis* through metal mesh.

which they grow, low yields and scattered distribution of the plants.

The principal rubber-producing plants which were exploited during the war in tropical America, either on a large scale or to a minor extent, were:

a) Species of *Hevea*, especially *H. brasiliensis* (Para rubber) of the Amazon basin, and *H. Benthamiana*, chiefly of the Upper Orinoco valley. (Family Euphorbiaceae).

b) Species of *Castilla*, especialy *C. elastica* (Panama rubber) and *C. Ulei*. (Family Moraceae).

c) *Manihot Glaziovii*, source of Ceará or manicoba rubber, from dry regions of eastern and northern Brazil. (Family Euphorbiaceae).

d) *Parthenium argentatum*, or guayule, from wild and cultivated plants, chiefly in dry regions of northern Mexico, California, Arizona and Texas. (Family Compositae).

e) *Hancornia speciosa* or mangabeira rubber of Brazil. (Family Apocynaceae).

f) *Sapium*, particularly *S. jenmani*, *S. aucuparium* and *S. hippomane*. The *Sapium* species occur in scattered distribution from the Guianas through Venezuela and Colombia to eastern Peru and Bolivia. (Family Euphorbiaceae).

g) *Micrandra*, especially *M. siphonioides* of British Guiana and southern Venezuela. (Family Euphorbiaceae).

h) *Cryptostegia*, especially *C. grandiflora* and *C. madagascariensis*. These plants were introduced from Madagascar into tropical America, especially Mexico and Haiti, but, because of their exacting cultural requirements and the difficulty and expense of extraction of the rubber, they were abandoned before the end of the war. (Family Asclepiadaceae).

Of these species, *H. brasiliensis* furnished the greatest portion of all natural rubber produced in tropical America during the war. Secondary in quantity produced was rubber from *H. Benthamiana*, *Castilla* species, guayule and manicoba. The other types of rubber listed were produced in small, almost negligible quantities. In the remainder of this paper the author will discuss certain features of rubber production in *Hevea brasiliensis*, *Castilla elastica*, *Sapium* and *Micrandra*, with which he has worked as an official of the Rubber Development Corporation.

Hevea brasiliensis

The tropical American exploitation of *H. brasiliensis* rubber during the war involved principally wild trees growing in the upper Amazon basin of Brazil, Peru and Bolivia. In addition, plantations of this species, established chiefly before 1920 in parts of Brazil, British Guiana,

Trinidad and some Central American countries, were brought into production after remaining unworked for 20 years or more.

Tapping methods for this species varied considerably in different areas. In some regions the herringbone method was employed. In this a vertical cut is made in the bark to a height of five to eight feet, with diagonal cuts draining into the vertical cut on both sides of the latter and extending from one-fourth to one-half the circumference of the tree. The latex flows from the diagonal cuts into the vertical cut, running down the vertical cut to a spout at the base of this cut, then dripping into a suitable container. The herringbone method, while producing fairly high yields, is not well adapted to tapping over a long period, to good bark regeneration or to continuing high production. In other areas a more effective method, the single half-spiral technique, was employed. In this a cut is made at an angle of about 30°, descending from upper left to lower right and extending for one-half the circumference of the tree; at the lower end of this cut a vertical cut is made to conduct the latex downward to a spout at the lower end of the vertical cut. The diagonal cut is made from upper left to lower right in order to intercept as many as possible of the latex tubes which extend spirally from upper right to lower left in the bark. In the half-spiral

FIG. 10. Addition of formic acid to strained *Hevea* latex for tray coagulation.

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Fig. 10. Addition of formic acid to strained *Hevea* latex for tray coagulation.

FIG. 11 (*Upper*). Tray coagulation of *Hevea* rubber. Foreground—coagulated rubber in trays. Upper left—coagulated rubber sheets. Upper right—power-driven mangle.

FIG. 12 (*Lower*). Passage of freshly coagulated *Hevea* sheet through crimping mangle.

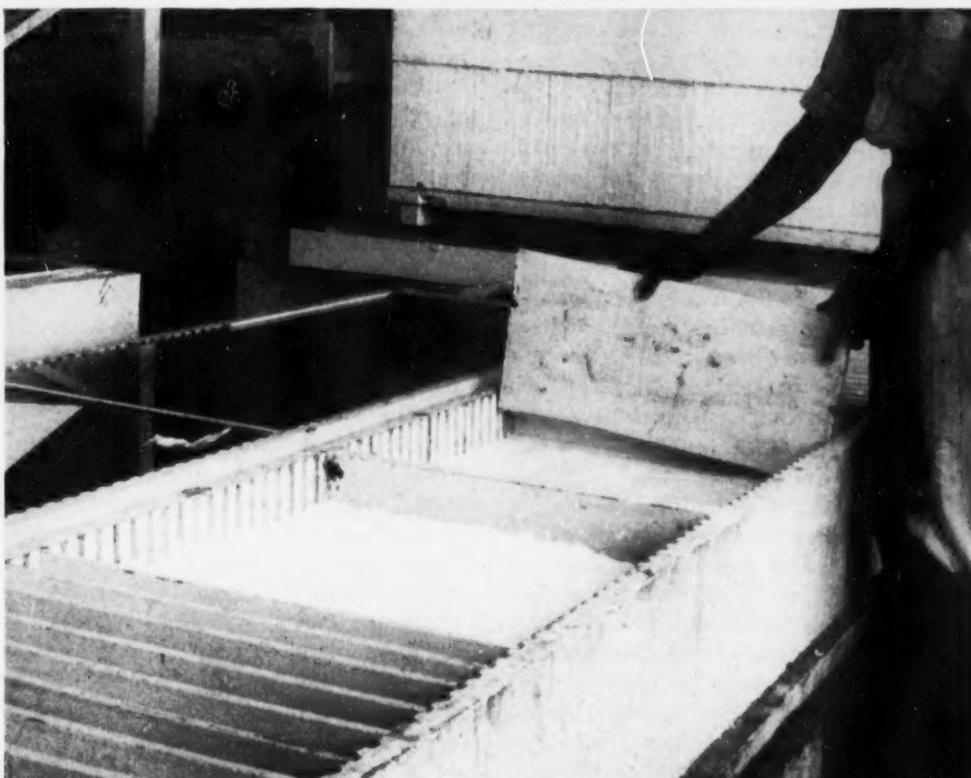


FIG. 13 (*Upper*). Tank coagulation of *Hevea* rubber: latex flowing into coagulation tank.
FIG. 14 (*Lower*). Tank coagulation of *Hevea* rubber: separation plates being inserted into wall slots of tank after addition of acid.

method the diagonal cut is made at a height which varies with the diameter of the trunk; in young trees the cut is placed so that its lower end is 18 to 20 inches above the surface of the soil, while in trees of large diameter the cut may be placed with its lower end 40 to 48 inches above the soil surface. On each tapping day the half-spiral cut is deepened by the removal of a shaving of bark about 1/16 inch thick. As a result of this fresh cut the latex begins to flow, coursing down the diagonal cut to the vertical cut. Tapping is usually done between dawn and 9:30 a.m., for, with the rising temperature of the air and of trunk tissues, the latex flow diminishes, then ceases within two to three hours after tapping. Certain precautions are taken to ensure the effectiveness of the half-spiral method: *a*) the tapping cuts must penetrate the inner bark, where the latex tubes are most abundant, without cutting through the cambium, for, if the cambium is injured and the wood exposed, regeneration of the lactiferous bark cannot occur; *b*) the tapping cuts must slope slightly inward to keep the latex within the cut and to prevent its running out of the cuts and down the bark; *c*) the thickness of bark removed on each tapping day should not exceed 1/16 inch in order to conserve the bark in the tapping panel for as long a time as possible. With proper tapping the bark is used up at the rate of not more than 1½ inches vertically per month, so that the tapping panel on one side of a tree should last for 1½ to 2½ years of tapping. When the lower end of the tapping cut approaches the soil line, the other half of the tree is tapped in the same fashion; during the period of 1½ to 2½ years of tapping the second half of the circumference, the first half regenerates new bark, so that, at the end of the tapping of the second half, the first half is again ready for tapping.

After each tapping, with cessation of latex flow, some latex coagulates in the half-spiral and vertical cuts. This rubber is collected by the tapper before the next tapping; this is called " scrap " and is washed, dried and shipped to be made into rubber cement, crepe rubber or other rubber products.

In the single half-spiral method, tapping is usually done on every tapping day. Since tapping cannot be done on rainy days and since rainy days are frequent in *Hevea* areas, the number of tapping days per month usually varies from 15 to 22 or 23. In dry seasons, when rains fall infrequently, tapping may be done on alternate days to avoid the danger of the trees' " drying up ". A variation of the half-spiral method is the double half-spiral technique, in which the tapping panel bears two parallel diagonal cuts at least 15 inches apart; each cut is tapped in the same manner as the single half-spiral cut. Double half-spiral tapping usually results in greater latex yield per tapping, but if used daily, may cause a cessation of latex flow in a few weeks. Thus the double half-spiral method is usually employed on an alternate day or once-per-three-day tapping schedule. This method is especially advantageous in areas with a shortage of tappers, for, using this technique, a single tapper may handle two or three " tasks " of trees, tapping them in rotation. When the labor supply is adequate, tappers commonly use the single-half-spiral method, tapping the trees in the same tasks on each rain-free day.

During the first few tappings of a tree the latex is very viscous and its flow usually slight. After six to ten or 12 tappings, however, the viscosity of the latex decreases and the flow increases, until after two or three weeks it reaches a generally sustained value. This so-called " wound response " is characteristic of most trees of this species.

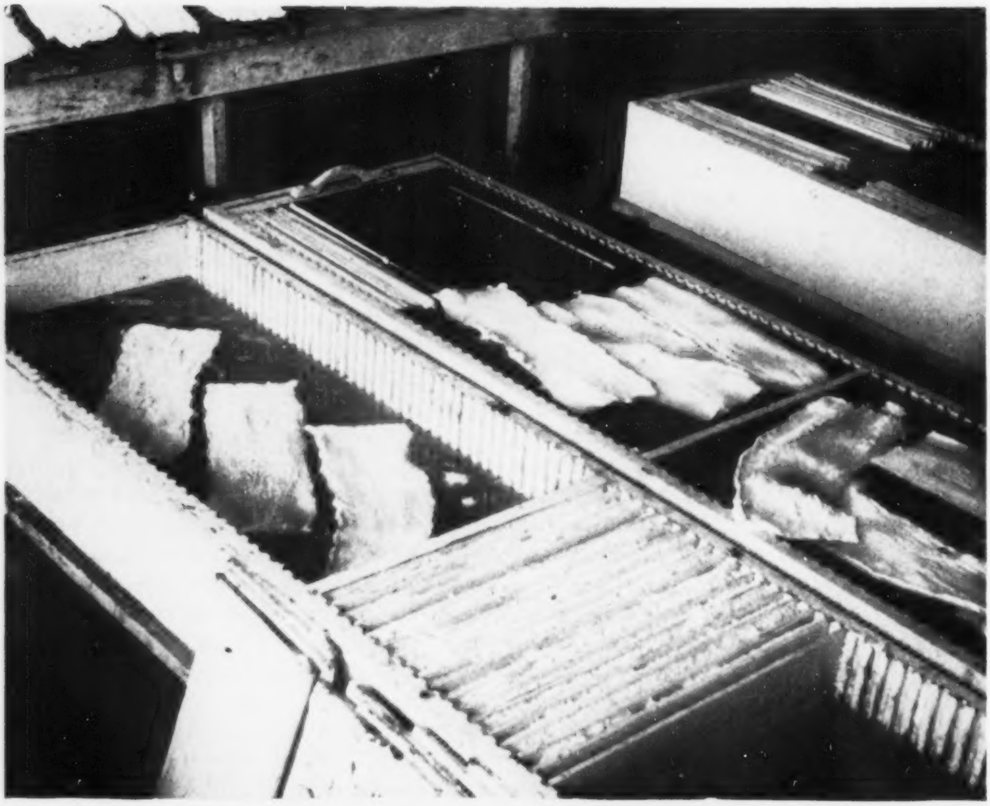
The yield of latex from Para rubber trees varies with many factors: age and size of the tree, chemical and physical

properties of the soil, temperature and precipitation conditions, and genetic factors. Trees which yield less than one ounce of latex per tapping are usually passed by until their yield increases. Wild trees of five-inch trunk diameters or greater commonly yield from two to seven ounces per tapping; occasional large trees may yield ten ounces or more per tapping. The author made a record of a large plantation tree in British Guiana, with a diameter of 4½ feet at five feet above the soil, which yielded from 12 to 17 ounces of latex per tapping (single-half-spiral method on alternate days) for a period of seven months. Latex yield is generally higher from plantation trees in well-drained soils, free of overgrowing extraneous vegetation, than from wild trees.

The dry rubber content of the latex of this species varies considerably. A number of determinations made on latex from individual trees in British Guiana indicated a variation in dry rubber percentage of 21 to 38 (after the wound reaction period). Average dry rubber content of latex from plantation trees in British Guiana appears to be about 31%.

After the flow of latex has ceased (usually by mid-morning), the tappers collect the latex from the receptacles of the individual trees and prepare to coagulate the rubber. Two common methods are employed in tropical American rubber areas: the older paddle-and-smoking method (described by Whaley in ECONOMIC BOTANY, April–June, 1948) which is widely used in the Amazon and Upper Orinoco basins and which produces balls of smoked rubber weighing from 40 to more than 125 pounds, and the acid-coagulation method used principally in *Hevea* plantation areas. The paddle-and-smoking method has several advantages over the acid-coagulation method: it requires no special equipment or chemicals, it may be performed at the tapping site and it simultaneously coagulates and smokes the rubber. Its major disadvantages lie in the lack of uniformity of the product, in the frequent inclusion of such foreign matter as bark chips, sand, leaves and pebbles in the rubber, and in the mechanical difficulties in tearing the balls apart and cleaning the rubber in factories. The acid-coagulation method produces a high grade of crude rubber in the form of easily packed and transported sheets which are free of foreign matter and which can be quickly utilized in factories without the expensive shredding and cleaning required in the processing of smoked ball rubber.

For acid coagulation, latex is brought by tappers from their " tasks " to a central coagulating shed. A few cubic centimeters of ammonia may be mixed with the latex if the tapping site is distant from the shed to prevent premature coagulation. When the latex reaches the coagulating shed, it is mixed with one or two parts of clean water, and the mixture is strained, first through a fairly coarse mesh, then through a fine mesh to remove all debris. The strained, clean, diluted latex is then placed in the coagulation receptacles and is thoroughly mixed with a very small amount of acid, usually formic or acetic. During the war, when irregular ship movements sometimes delayed formic acid shipments, lime juice was used effectively as a substitute coagulant. The coagulation receptacles are of two general types: shallow pans or trays made of metal or hard woods, such as greenheart, and large coagulating tanks. The trays, which are usually three to five inches deep, ten to 12 inches wide and about three feet long, are used chiefly on small plantations whose daily latex production averages 50 to 75 gallons. The latex-acid mixture is poured into the trays to a depth of two to three inches, and the trays are carefully stacked, then covered to prevent debris from falling into them. Coagulation begins quickly and is usually com-



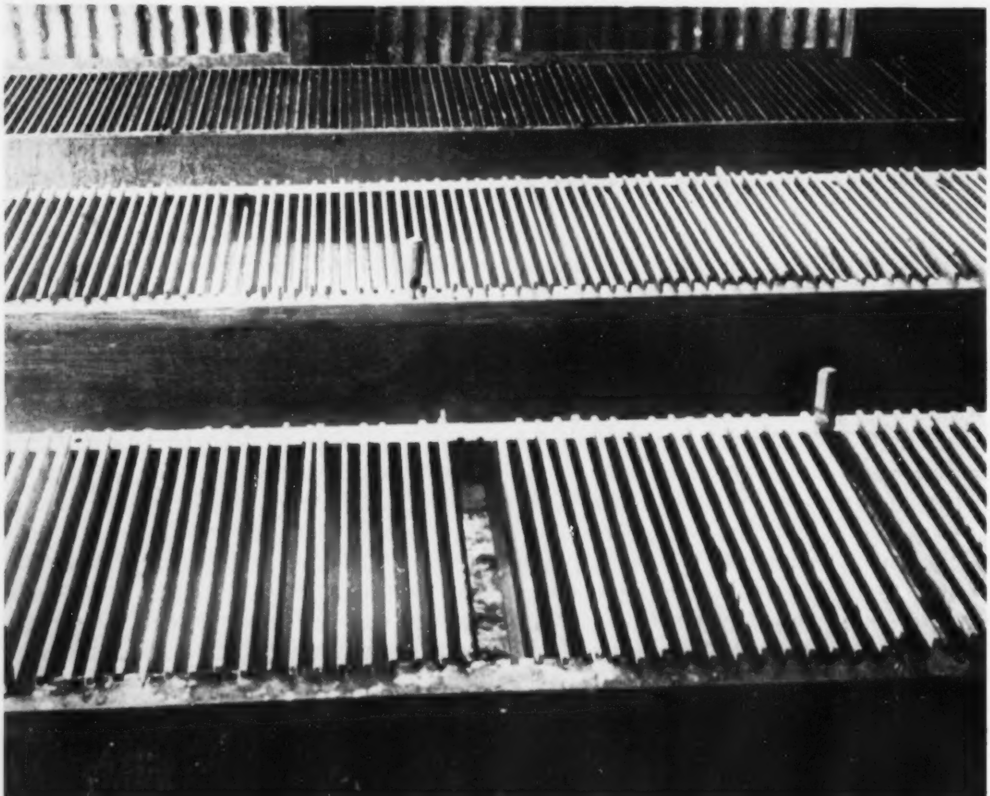


FIG. 15 (*Upper*). Tank coagulation of *Hevea* rubber: coagulated rubber floating on surface of serum after removal of separation plates.

FIG. 16 (*Lower*). Battery of three coagulating tanks.

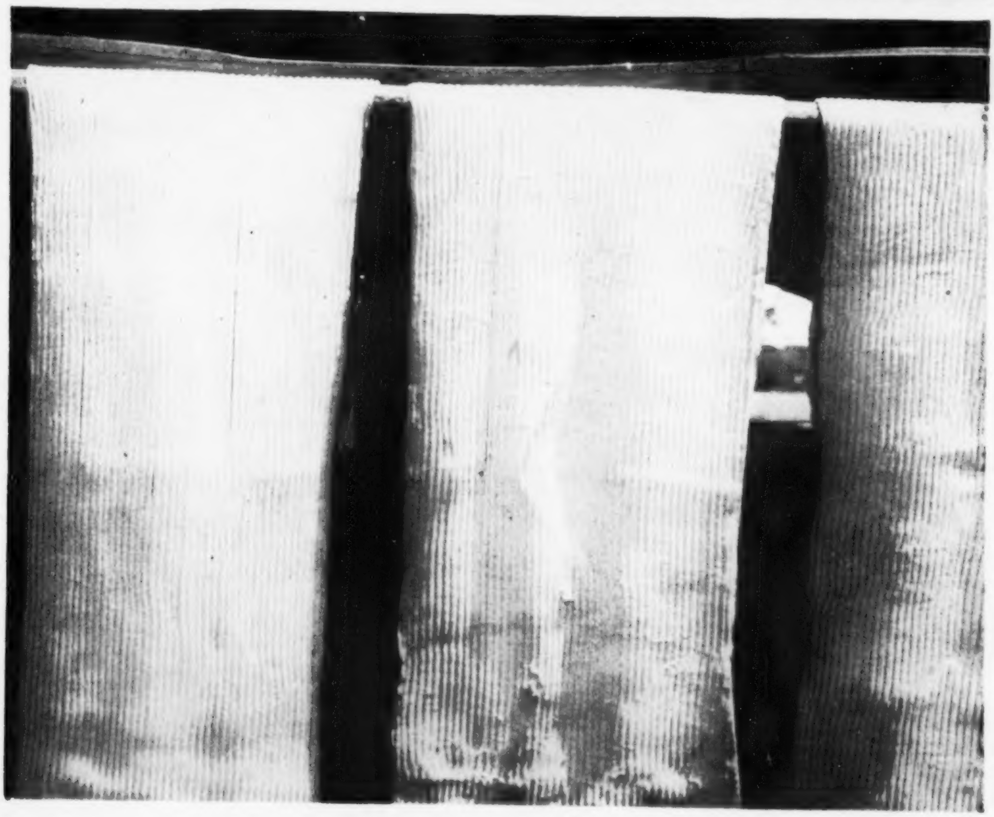


FIG. 17 (*Upper*). Mangling *Hevea* rubber sheets. Left—sheets after passage through mangle. Right—sheets before passage through mangle.

FIG. 18 (*Lower*). Sheets of *Hevea* rubber after crimping.

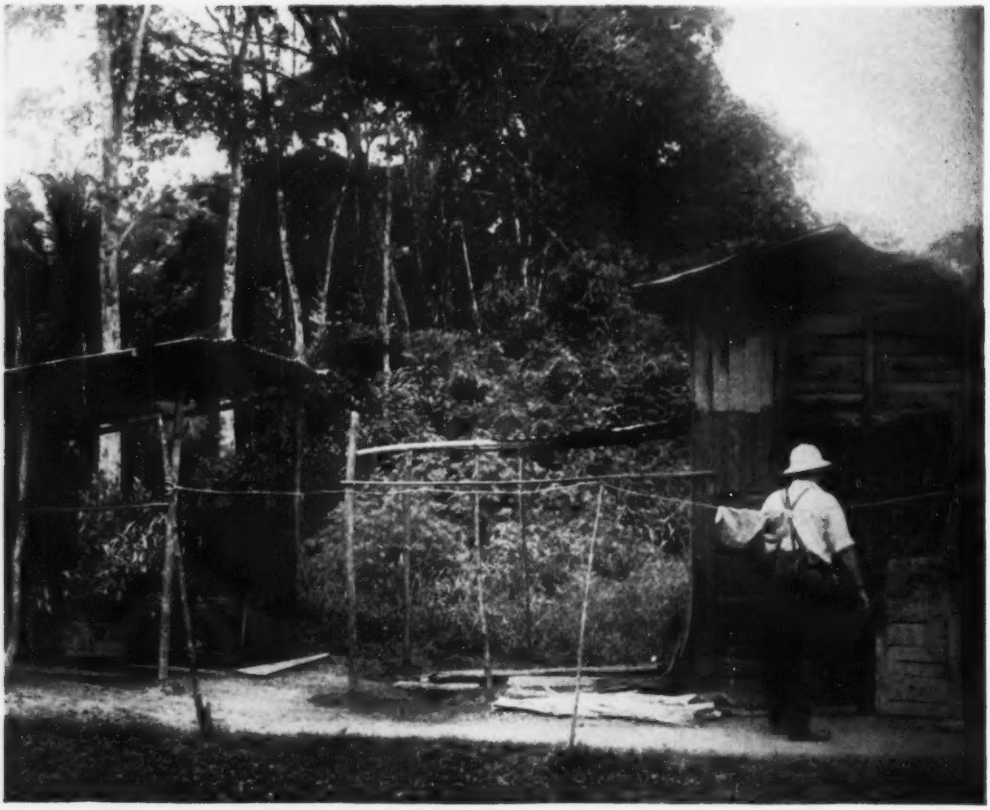


FIG. 19 (*Upper*). Coagulating shed and smokehouse on small *Hevea* plantation, British Guiana.
FIG. 20 (*Lower*). Coagulating shed and smokehouse on large *Hevea* estate, British Guiana.

FIG. 21 (*Upper*). Coagulating shed (left) and smokehouse on medium-sized *Hevea* estate (5,000 trees). British Guiana.

FIG. 22 (*Lower*). Baling *Hevea* smoked sheets.

pleted within three to five hours, the coagulated rubber appearing as a soft, white, spongy sheet about one inch thick floating on the surface of the aqueous portion of the latex-water mixture. Either late the same day on which the latex is poured into the trays, or the following morning, the spongy rubber is carefully lifted from the trays for mangling. During the war on many plantations the coagulation and mangling were performed by the wives and children of the tappers. The soft sheets are passed through a mangle with smooth cast-iron rollers which squeeze out a large percentage of the water in the rubber and flatten the sheets to a thickness of about one-eighth inch. The sheets may then be hung in a shaded place to air dry for 24 hours, after which they are suspended in a smokehouse. On some plantations the sheets, after the first mangling, are passed through a crimping mangle, the rollers of which are grooved or otherwise sculptured. Sheets passed through a crimping mangle are stamped with the design of the rollers. The purpose of crimping is twofold: to increase the surface of the sheet in relation to its volume, as a result of which drying of the sheet is accelerated, and, in some areas, to mark the sheets with a readily identifiable design bearing the initials or brand of a plantation. After being crimped the sheets are hung to dry superficially in air, then are placed in a smokehouse. Usually only larger plantations utilize both smooth and crimping mangles. Mangles may be hand operated or driven by gasoline engines or other power sources.

Coagulation tanks are used chiefly on estates with a daily production of more than 75 gallons of latex. Such tanks, though varying in size, have common structural features: they are usually 24 to 30 inches wide and about 18 inches deep, and their lateral inner walls have vertical grooves about three-fourths inch apart. Strained latex mixed with acid is allowed to flow into the tanks, then wooden or metal plates, made to slide downward into the wall grooves, are inserted. The rubber then coagulates in sheets between these plates, and, when coagulation is complete, the plates are lifted out of the grooves, the rubber sheets floating on the surface of the "serum". The sheets are then carefully lifted out, mangled, superficially air dried and transferred to a smokehouse. Various aspects of tray and tank coagulation are shown in the accompanying photographs.

The smoking of rubber has two functions: it hastens the drying of the sheets and has a preservative effect which inhibits the growth of fungi on the sheets during storage and transit. Rubber sheets, which require from four to six weeks for partial drying in the humid outdoor air of rubber regions, may be completely dried in as short a time as four days in a well-designed smokehouse. During the war a variety of structures was used for smoking rubber sheets; some were mere sheds constructed of scrap lumber and flattened tin cans, others were carefully built of sound timbers and galvanized metal sheeting. The essential requirements of a smokehouse are a furnace for the slow combustion of fuel, chiefly wood, and sufficient circulation to carry warm smoke to all parts of the structure. On larger estates the smokehouses are usually tall structures, sometimes with five or more floors, or they may consist of a series of separate rooms on the same level. In a tall smokehouse a furnace beneath the lowest floor provides the smoke, and the floors are perforated or open, except for catwalks, so that the smoke and heat may ascend unobstructed. The rubber sheets, after mangling and superficial air drying, are hung on horizontal bamboo rods or wood strips. Care must be taken to insure a continuous movement of warm smoke through the house and to avoid

excessively high temperatures which cause rubber to become soft and sticky. As they undergo smoking the sheets lose their opaque white appearance and become translucent and amber-colored; at this stage the sheets are removed from the smokehouse to prevent over-smoking. The smoked sheets are then packed in boxes or bales for shipment to manufacturing centers. At some time after smoking the rubber is graded on the basis of its cleanliness, dryness, degree of smoking and other qualities. The highest price paid for any type of rubber is that paid for " No. 1 ribbed, smoked Para sheet ".

In addition to smoked balls and sheets, *Hevea brasiliensis* rubber was produced in tropical America in other forms during the war. Among these was scrap rubber of two types: tree scrap, removed from tapping cuts and spouts, and earth scrap, from latex coagulated on the soil. Because of its dark color and reduced elasticity, earth scrap commanded a lower price than tree scrap. On a few large estates tree scrap was converted into crepe rubber by a creping machine, the working parts of which are two rollers with sharp ridges. These rollers press tightly against each other and rotate at different speeds, exerting a shredding effect upon the washed clean scraps. The small shreds, as a result of this tearing action and pressure, are welded together in long bands of rough-textured crepe rubber which are then dried and smoked, as are rubber sheets.

Many other interesting features of rubber production by *H. brasiliensis* cannot be described in detail in this paper. In many trees there is a sharp decrease in latex yield at the time of leaf fall, which usually occurs once per year, and tapping operations are often suspended during the brief leafless period until a new crop of leaves develops and the latex yield begins to rise. Another interesting feature of *Hevea* is its ability to store large amounts of latex, or of organic compounds from which latex is produced, in its roots; stumps of trees whose upper portions have been cut away or have fallen may, with suitable tapping, continue to yield appreciable quantities of latex for many months. Similarly the girdling of a trunk above a tapping panel commonly has no depressing effect upon latex yield for a period of several months to a year, indicating the prior storage of latex or latex precursors in large quantities in the trunk base and roots, or possibly the downward translocation of such materials in xylem.

Another interesting feature of the Para rubber tree is its sensitiveness to soil moisture conditions. The author made measurements of latex yields of trees in eastern British Guiana in a low-lying plantation which was flooded after a breach in a dike which separated the estate from a river; the flood waters covered the soil to a depth of about four inches and remained standing on the soil for about three weeks before drainage was accomplished; within six days after the water entered the plantation the average latex yield decreased to about 55% of the pre-flood yield. The author observed also that trees growing in rather dry soil responded quickly to irrigation, the latex yield rising 32% within ten days after the irrigation water was admitted.

A serious problem in war-time rubber exploitation in tropical America was damage to tapping panels. Since the boom days of tropical American rubber, a new generation of laborers, many of them unacquainted with tapping methods, had grown up and required training in proper tapping methods. Because of the urgency of the rubber situation, some of these laborers began tapping before they had thoroughly learned the importance of avoiding bark injury. As a consequence of this factor, and also as a result of the desire of some workers

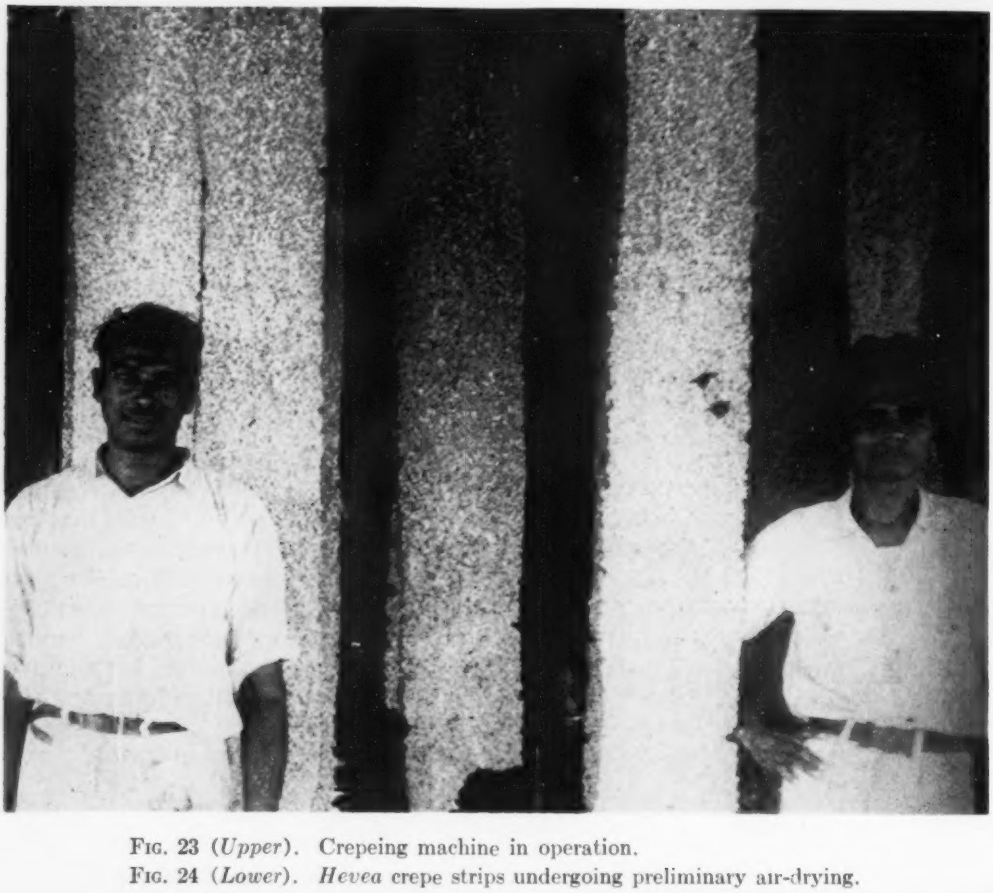


FIG. 23 (*Upper*). Crepeing machine in operation.
FIG. 24 (*Lower*). *Hevea* crepe strips undergoing preliminary air-drying.

FIG. 25 (*Upper*). Young *Castilla elastica* trees on cacao estate, Venezuela.

FIG. 26 (*Lower*). Base of *Castilla* trunk, showing tapping cuts. Notice coagulated rubber on tapper's clothing.

to tap a large number of trees in a brief time, destructive tapping frequently occurred, which completely stripped trees of their bark and cambium, preventing bark regeneration and thus ruining trees for further tapping. This injury to trees was especially important on plantations, the owners of which wished to protect their trees in the event that tropical American rubber exploitation might continue for a number of years after the war. The author found that a few older tappers in British Guiana plastered damaged tapping panels of *Hevea* trees with a mixture of soil and manure which they alleged would promote lateral growth of new bark from islands of bark left in damaged panels. Although there appeared to be a slight beneficial effect of this treatment in some trees, such effect was too little to be measured with certainty. In an effort to find some method of promoting bark healing, the author coated badly damaged tapping panels with indoleacetic and naphthaleneactic acids in concentrations of 10, 25, 50, 100, 200, 500, 1000 and 2500 parts per million in lanolin. These treated panels were observed for four months, during which added bi-weekly applications of the lanolin-auxin pastes were made on some trees. In no instance was there any evidence of accelerated healing of damaged bark; in a few trees occasional adventitious roots appeared from the lower portions of bark islands covered by the paste.

Other species of *Hevea* in the Amazon and Orinoco basins were also exploited during the war. Of these, *H. Benthamiana* was second to *H. brasiliensis* in amount of rubber produced, but was far short of the latter. Most of the rubber from *H. Benthamiana* came from the Upper Orinoco basin. Negligible amounts were obtained from *H. lutea*, and attempts to obtain rubber from *H. guianensis* failed, partly because of low yields, extremely scattered distribution and the extremely sticky nature of rubber from this species.

Castilla elastica

Castilla elastica, a native of southeastern Mexico, Central America and the northwestern part of South America, has been a local source of rubber intermittently since pre-Columbian times. It is probable that the first rubber objects seen by white men were fashioned by aboriginal Americans from the latex of this species, known commonly as "Panama rubber". The trees have been (and are) tapped in their wild state, and have been established in plantations in several countries of Central America and northern South America. Local tapping of this species has persisted even during periods when there was no export market for the product, the rubber being used locally in waterproofing fabrics, in rubber cement and in the soles of sandals. Because of their rapid growth, their large size and the extensive shade cast by their spreading branches and large leaves, Panama rubber trees have been extensively planted as shade-trees on cacao estates. Most of the trees tapped in Venezuela and Trinidad during the war, for example, grew on cacao plantations.

Three methods of tapping Panama rubber trees are used: *a*) destructive tapping, in which the trees are cut down and their bark cut in many places to drain all possible latex from the tree; *b*) machete tapping, in which machete cuts are made in close proximity in the bark, with the result that the latex runs down the bark in many irregular streams, coagulating on the bark, from which it is removed by hand as tree scrap; *c*) herringbone tapping, done with a special *Castilla* tapping knife or a machete, in such fashion that the latex runs down a central vertical cut, from lateral cuts, to a spout and then into a container. Herringbone panels are usu-

ally made by tappers standing on the ground and reaching to a height of seven or eight feet. Less frequently tappers climb to a height of 25 to 40 feet on the trunk, supporting themselves on a woven fiber seat held by a rope which passes around the tree and cutting a herringbone panel from the maximum height to the base of the trunk. In war-time operations it proved difficult to induce tappers in many areas to climb the trees to cut these king-size herringbone panels; there were, however, usually a few brave individuals who, lured by the high yields obtained by this method, became proficient in climbing the trees.

The irregular hacking of bark by machetes, although it produces a fair yield of tree scrap, causes the bark to become very rough and knobby as the small cuts heal, and thus renders it unfit for possible subsequent herringbone tapping. A herringbone panel cut to a height of seven or eight feet induces a good flow of latex, a large tree sometimes yielding more than two quarts of latex at a single tapping. Much larger yields are obtained when the herringbone panel is extended to a height of 25 or more feet; in Trinidad the author observed yields of nearly five gallons of latex from individual large trees at a single high-herringbone tapping. Destruction of trees to obtain all the latex in their tissues is, of course, a wasteful procedure and was generally discouraged during the war, at least in the case of plantation trees; in some areas, however, trees were cut down for their latex, since the rubber emergency seemed to justify such exploitation.

When a tree is tapped by the herringbone method, the latex flows from the cuts for several hours, infrequently over night, and the tree then becomes " dry "; that is, deepening or extension of the cuts results in no immediate further flow of latex. Trees tapped by a low herringbone panel ordinarily do not yield sufficient latex to justify a second tapping until after three or four months; thus trees tapped by this method are ordinarily tapped only three or four times per year. In trees tapped by the high herringbone method, productive tapping can be done only two or three times per year. This feature of latex behavior is one of the factors which has prevented Panama rubber from becoming a competitor of Para rubber.

Coagulation of *Castilla* latex is ordinarily accomplished by one of three methods: *a*) the latex may be poured in thin layers on boards or on a wooden floor, the rubber hardening slowly as a result of exposure to air; *b*) the latex may be mixed with an extract of various species of moonvine (chiefly *Ipomoea bonanox*), prepared by crushing the stems and leaves in water; *c*) the latex may be mixed with a solution of cheap laundry soap. The first method is unsatisfactory because it is very slow and thus requires a large amount of space for the pouring out of the latex; further, latex thus handled inevitably collects debris which lowers both quality and price of the rubber. The second method is moderately unsatisfactory, although it is more rapid than the first; its principal disadvantage lies in the time and effort which it requires for locating, collecting and extracting the moonvine plants. The soap coagulation method is most rapid and most satisfactory, for it produces very clean rubber. The latex is poured into trays from three to six inches deep, and a small amount of soap solution, prepared by dissolving about one-half pound of soap in a gallon of water, is thoroughly mixed with the latex. Coagulation begins within 30 seconds and is usually completed within five minutes. The soft slabs of coagulated rubber are then lifted from the trays, washed briefly in clean water, then passed through a mangle and hung to dry in air or in a smoke house. On many small estates

Fig. 27 (*Upper*). Rolling out freshly coagulated *Castilla* sheet.
Fig. 28 (*Lower*). Rolled *Castilla* sheet.

FIG. 29 (*Upper*). Machete-tapping of felled *Micrandra* tree, Venezuela.

FIG. 30 (*Lower*). Herring-bone panel on *Micrandra* trunk. Latex has oozed into diagonal cuts, but none has run into vertical channel.

which cannot afford mangles and in remote areas to which the heavy mangles cannot be conveniently transported, the freshly coagulated sheets are rolled out on tables or benches with rolling pins fashioned on the scene from local hardwoods. Freshly coagulated Panama rubber is usually buff-colored and darkens as it dries, the dried rubber becoming black. The sheets cannot be exposed to the sun or very warm smoke during drying, for under these conditions they become very sticky. Well dried *Castilla* sheets are usually more sticky than those of Para rubber, chiefly because of their higher resin content; the resin content of sheet *Castilla* rubber usually varies from 4% to 9.5%, in contrast with that of Para rubber sheets, which rarely exceeds 3%. The relatively high resin content of Panama rubber is a factor which has militated against its becoming an important rubber on world markets.

An interesting feature of latex behavior in *Castilla* trees is the pressure under which the latex occurs in the lactiferous tissue. Frequently this pressure is so great that the latex spurts out for a distance of several inches when the knife blade cuts the lactiferous tissue. One of the accompanying photographs shows a tapper whose shirt and trousers have a pebbled, crepe-like appearance, the result of air coagulation of drops of latex which spurted onto the tapper's clothing. During the war tappers frequently increased their earnings by adding their rubber-laden clothing to the rubber which they produced.

Other species of *Castilla* were exploited during the war, but most *Castilla* rubber was derived from *C. elastica*. Of other species exploited, *C. Ulei* of the Upper Amazon basin was the principal source of this type of rubber. Exploitation of *Castilla* rubber will likely continue on a local basis, as it did before the war, but this rubber will probably never be exported from the tropical American countries, except in the event of another war-induced rubber shortage, partly because of its high resin content, partly because of its low yield as compared with that from *H. brasiliensis*, and partly because of the fact that the trees can be tapped only three or four times per year.

Sapium rubber

The tapping of *Sapium* trees was a sporadic operation during the war and was carried out chiefly in parts of Venezuela, Colombia, Peru and adjacent areas of northwestern South America. At least 16 rubber-producing species of *Sapium* are known to occur in South America, but only six or seven of these were tapped during the war. Principal species tapped were *S. aucuparium*, *S. verum*, *S. peloto*, *S. hippomane* and *S. jenmani*. Although attempts were made over extensive areas to achieve a high production of *Sapium* rubber, the total amount of rubber obtained from species of this genus was small as compared with that from *Hevea* and *Castilla* species. Several factors were responsible for this rather unsatisfactory production of *Sapium* rubber: the scattered distribution of trees, the hardness of the bark which renders tapping difficult, the extreme variability among individuals of a species in yield and in dry rubber content of latex, and the inability of the trees to withstand frequent tapping such as that used on *Hevea*.

The author's experience was chiefly with *S. jenmani* in British Guiana. Trees of this species occur in a very scattered distribution, chiefly in the western part of the colony and on the many islands in the Essequibo river. The hard bark of this species made tapping a slow and laborious process with tapping knives, which are quickly dulled, and only with machetes could fairly rapid tapping be accomplished. Experimental tapping showed that best yields of rubber were

obtained with the herringbone method; single and double half-spirals were unproductive. One of the reasons for unsatisfactory yields from this species is the very high viscosity of the latex; in only about 25% of the trees tapped was the latex sufficiently fluid to flow from the cuts into a receptacle. In the other 75% of the trees the thick latex simply oozed out into the tapping cuts, in which it coagulated, usually within 12 to 16 hours, forming scrap rubber which was then stripped from the cuts. Deepening the cuts within two or three days after the first tapping caused little additional flow of latex. Average yield during the tapping experiments was three pounds of dry rubber per tapper per day, an insufficient quantity to reimburse tappers who could produce from ten to 15 pounds of dry *Hevea* per day on nearby plantations. A few tappers persisted for some weeks in tapping *Sapium*, but the amount of rubber produced was small, and they soon abandoned their work. Greater success was reported with *S. jenmani* rubber in Venezuela and Colombia, although quantities produced in these countries were not large. Because of the scattered distribution of the trees, of the variability in yields, of the difficulty in cutting the bark and of the usual production of the rubber as scrap, *S. jenmani* exploitation in British Guiana contributed very little to the rubber output of the colony.

Micrandra rubber

Several species of *Micrandra* occur in a very scattered distribution in South America, especially in the Upper Amazon and Orinoco basins. *Micrandra* rubber, like that of *Sapium*, is of good quality. *Micrandra* species have never constituted an important source of rubber, however, partly because of the insufficient concentration of trees, partly because of varying yields and partly because of the distribution of the trees in areas of sparse populations. During the war the author conducted a number of tapping experiments on trees of *M. siphonioides* in the Paragua river valley of the Orinoco basin. As in *Sapium*, the latex was very viscous and in most trees oozed out into the tapping cuts without flowing down the vertical channel of the herringbone panel into a container. In a few trees small amounts of latex were caught in the latex cups, but, for the most part, only scrap rubber was obtained. One tapping contractor, using aboriginal Indian tappers, exploited *Micrandra* rubber in Venezuela for several months, but finally, because of transportation difficulties in this remote area and of his slender profit margin, he abandoned his undertaking. During his operations he obtained fair yields of rubber by felling trees and incising their trunks.

War-time experience with *Sapium* and *Micrandra* rubber leads to at least two conclusions: that wild rubber trees of very scattered distribution cannot be satisfactorily exploited, even in a time of great emergency, and that rubber-producing species which yield chiefly scrap, without a good flow of latex coagulable in sheets or blocks, are not susceptible of even moderate production.

Small Grains for Starch Production

Wheat, sorghum, rice, barley, oat and rye grains are actual or potential raw materials for the industrial production of starch, but only the first three are so used. All six contain about 60% to 70% starch, and yield oil and protein as valuable byproducts of starch manufacture. Successful competition of these grains with the present major industrial sources of starch—corn, potatoes and cassava—depends on a number of factors, including comparative costs of the raw materials, efficiency of processing methods, and value of the byproducts.

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Cereal grains are excellent sources of starch, since they contain about 60% to 70% of this carbohydrate. In the United States most starch is produced industrially from corn which is here the economically preferred source. In some other countries, root crops, such as potatoes or cassava, compete favorably with cereals on an economic basis and are chiefly used for starch production.

Among the cereal grains, wheat, rice and sorghum are processed on a lesser scale than corn for the separation of starch. Barley, oats and rye are also possible sources of commercial starch. This paper deals with these six grains which are minor or potential raw materials for industrial production of starch.

Botany

Wheat (*Triticum vulgare* (Vill.) Host.), sorghum (*Sorghum vulgare* Pers.), rice (*Oryza sativa* L.), barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), and rye (*Secale cereale* L.) are members of the grass family (Gramineae). All are of prehistoric origin. The grain, or caryopsis, is the typical fruit of this family. It consists of the germ, endosperm, seedcoat and pericarp, and sometimes a nucellus.

Production

Wheat, barley, oats and rye are produced chiefly in temperate and cool climates, while sorghum and rice are widely cultivated in tropical, sub-tropical and warm temperature areas. Sorghum, which is more drought-resistant than corn, is especially profitable in some regions, such as southwestern Kansas and the panhandle regions of Texas and Oklahoma in the United States, where rainfall is low. In that area it is also often planted when winter wheat fails to survive in good stand. On fertile irrigated soil, grain sorghum yields are equal to those of corn.

Statistics for the 1948 production of the small grains are summarized in Table I. That is the most recent year for which such data are available. The estimated annual production since 1935 is shown in Table II. Data for sorghum are incomplete in both tables because statistics are not fully available for this grain.

[1] One of the laboratories of the Bureau of Agricultural and Industrial Chemistry, Agricultural Research Administration, U. S. Department of Agriculture.

TABLE I

PRODUCTION OF WHEAT, SORGHUM, RICE, BARLEY, OATS AND RYE, 1948 (1,000 BUSHELS)

Grain	World	U. S.	North America	South America	Europe	Asia	Africa	Oceania[2]
Wheat[1]	6,390,000	1,288,406	1,701,000	270,000	1,455,000	1,593,000	148,000	195,500
Sorghum	(863,288)[3]	131,644[1] (48,849)[3]	....	(14)[3]	(7,542)[3]	(705,187)[3]	(101,696)[3]	....
Rice (rough)[1]	7,473,000	81,170	106,301	158,943	56,436[4]	6,954,326[4]	174,152	4,585
Barley[1]	2,384,000	317,037	478,000	48,000	635,000	757,000	127,000	19,083
Oats[1]	4,205,000	1,491,752	1,853,000	75,000	1,360,000	98,000	22,000	36,500
Rye[1]	1,665,000	26,388	51,728	9,000[5]		15,500[6]	....	....

[1] Preliminary (24).
[2] Including Australia and New Zealand.
[3] Averages for 1934–38 (1).
[4] Exclusive of U.S.S.R.
[5] Argentina.
[6] Turkey.

Harvesting

Methods of harvesting cereal grains are well known. They vary greatly, depending upon the extent of mechanization of agriculture in the different regions of cultivation. The most recent development is probably the combine harvesting of grain sorghum in the United States. For this purpose, varieties have been especially bred which attain the desired height of about three feet at maturity.

Chemical Constitution

Typical proximate analyses of wheat, sorghum, rice, barley, oats and rye are given in Table III. Cellulose, hemicelluloses and pectic substances account for a portion not determined.

Starch. The major chemical constituent of the six cereal grains under consideration is starch. This occurs in the form of small granules which vary in size and shape with the plant source (Fig. 1). The granules of rice and oat starches are naturally compound, *i.e.*, several simple granules are closely packed into one rounded mass. These compound granules break up readily during processing, hence the simple granules are more often observed.

These granules are part of the food reserve stored in the endosperm for nutrition of the seedling during germination. Some starch, of smaller granule size, also occurs in the germ, and in some genera (*Sorghum*, for example) in the pericarp or hull. It is the endosperm starch, however, which is separated industrially.

In the endosperm the starch granules lie more or less embedded in a matrix which is largely proteinaceous in nature (Fig. 2). Commercial production of starch depends upon the disintegration of this network to free the granules.

Prime-quality starch contains approximately 0.1 to 0.7 percent oil and related substances, and about 0.1 to 0.4 percent protein; it is white or very nearly white,

TABLE II

ESTIMATED ANNUAL WORLD PRODUCTION OF WHEAT, SORGHUM, RICE, BARLEY, OATS AND RYE (24). (1,000 BUSHELS)

Grain	Average		1946	1947
	1935-39	1940-44		
Wheat	6,021,000	5,735,000	5,720,000	5,775,000
Sorghum	863,288[1]	....	....	....
Rice	7,323,000	6,994,000	6,972,000	7,219,000
Barley	2,364,000	2,325,000	2,087,000	2,192,000
Oats	4,367,000	4,300,000	3,920,000	3,740,000
Rye	1,733,000	1,500,000	1,380,000	1,520,000

[1] 1934-1938 (1).

and, for food uses, should have no apparent flavor.

Protein. Protein, commonly called gluten, is a byproduct of starch manufacture. It is more or less contaminated with the smaller starch granules and with fragments of fiber.

Oil. Oil is an important constituent of the germ and occurs also in the aleurone cells, the outermost cells of the endosperm. Only the oil from the germ is recoverable under existing methods. When germ separation is part of an industrial process, oil is usually removed from the germ by pressing or by solvent extraction.

Sugar and Ash. These minor constituents are not deliberately separated during processing for starch. To a large extent, however, the sugar and ash go into the steep water when the wet-mill process is used.

Processing

The main steps in processing a cereal grain for starch production are separation of the hull and germ from the endosperm, and removal of the starch from the endosperm cells. There are several different ways in which these results are accomplished.

Wet Milling. Processing by wet milling is the method used for corn starch production (2, 13, 22) and, with minor modifications, is applicable to the other cereal grains.

The grain is steeped for 18 to 48 hours in a 0.1% to 0.4% solution of sulfur

TABLE III

CHEMICAL COMPOSITION OF WHEAT, SORGHUM, RICE, BARLEY, OAT AND RYE KERNELS (PERCENT, MOISTURE-FREE BASIS)

Grain	Starch	Protein	Oil	Sugar	Ash
Wheat[1]	67.0	12.8[2]	1.6	2.36	2.25
Sorghum[1]	72.6	12.2[3]	3.4	1.46	1.65
Rice (Husked)[4]	77.2[5]	8.9	2.0	....[5]	1.9
Barley[1]	71.8	10.3[2]	1.55	....	1.71
Oats[1]	64.0	12.9[2]	8.68	....	1.93
Rye[1]	59.1	14.2[2]	1.55	....	1.96

[1] Data given are for single samples of representative varieties; analyses by Analytical and Physical Chemical Division, Northern Regional Research Laboratory.

[2] Nitrogen × 5.7.

[3] Nitrogen × 6.25.

[4] (18).

[5] Total carbohydrate is given under starch heading.

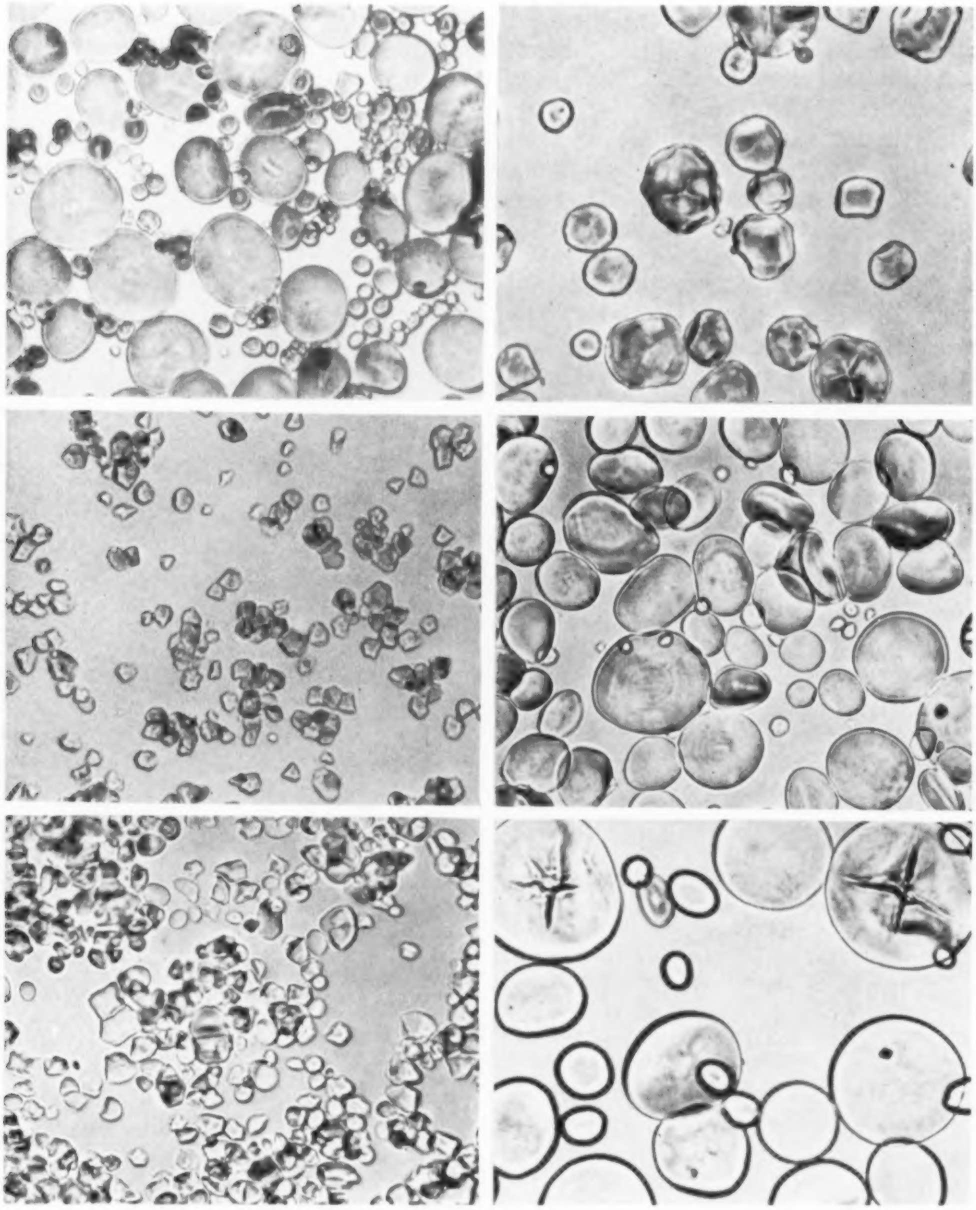

FIG. 1. Starch granules from seeds of: Left to right, top: wheat, grain sorghum; center: rice, barley; bottom: oats, rye. Magnification 500×.

dioxide at a temperature a few degrees below the initial gelatinization temperature of the starch. (The initial gelatinization temperature of a starch is that temperature at which the granules begin to lose their birefringence when heated in water.) The steeping process softens the grain for milling and breaks down the proteinaceous matrix in which the starch granules lie embedded within the endosperm cells (6, 7).

Steeped grain is coarsely ground in

vertical degerminators or attrition mills which break the kernels and tear the hull and germ from the rest of the grain (the endosperm). The germs are then separated from the endosperm pieces and hulls by flotation. The remaining slurry of hulls and coarse particles of endosperm is passed onto grit reels, where it is de-watered.

The mixture of endosperm and hull particles is then passed through horizontal upper-runner buhr mills to reduce the size of the endosperm particles and to break the cell walls so that the starch is freed. The cell walls and pieces of hull are largely removed as coarse fiber by passing the ground material in a slurry over shaker screens. The remaining slurry contains fine fiber with the starch and protein. The fine fiber is removed by passage over shaker screens. The starch and protein are then separated from each other by gravity, as the starch has the greater density. Either long slightly inclined tables or centrifuges are used for making the separation. The trend is away from tabling and toward centrifuging (22). Centrifuges are used to purify the starch further and to recover some starch which during the first separation remains in the protein, or gluten fraction. Throughout the wet-milling process fractions containing incompletely separated material are returned to the operation or given a second pass to obtain efficient separation. Starch, fiber and gluten fractions are dried. Oil is expressed from the germ or separated by solvent extraction. The remainder of the germ is dried.

Industrial applications of this process have been made to wheat (14, 15, 20) and to sorghum (10, 21, 23). The newest wet-milling plant, recently constructed in the United States to process sorghum, uses disintegrators and double revolving-plate attrition mills, also called re-pulpers, in place of buhr mills (23). Centrifugals entirely replace starch tables in this installation.

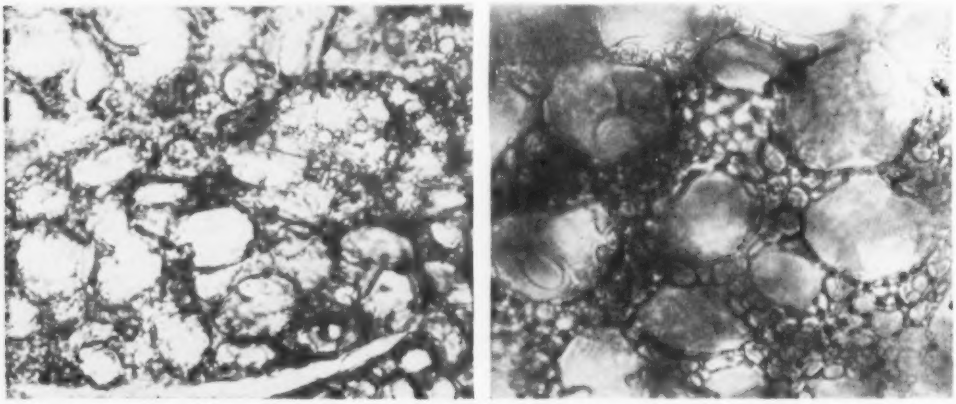

FIG. 2. Portion of endosperm with starch granules removed, showing proteinaceous matrix which surrounded the granules. Left: wheat; right: barley. The heavy white structure at the lower edge of the left photomicrograph is a cell wall. In both wheat and barley large and small starch granules occur in the same cell; hence large and small openings are left in the proteinaceous matrix when the granules are removed. Magnification 500×.

Laboratory studies have shown that the wet-milling process as applied to corn does not lead to good starch recovery when used for barley, oats and rye (16). Doubtless these three grains could be wet-milled for starch production if the conventional process were suitably modified. Up to the present time, however,

barley, oats and rye have not been used to any significant extent for starch production.

Methods of Producing Wheat Starch from Flour. Wheat starch has for many years been produced by the Martin process. The raw material is first or second clear grades of flour, rather than the whole grain. Flour is mixed with water to give a dough of about the stiffness of bread dough. This is allowed to stand for an hour or longer to permit the protein to take up water and become cohesive, after which it is kneaded mechanically under jets of water which wash out the starch. The latter is purified by sieving, followed by gravity separation and centrifuging before drying. The Martin process is a batch method.

In a second method employed for producing wheat starch from flour, the starch is washed out of a thinner dough than that used in the Martin process. This is a continuous process. The dough is mechanically kneaded to agglomerate the gluten during the washing (4). Sieving and centrifugal separation are used to purify the starch.

The batter process for the separation of starch and wheat gluten from wheat flour was developed at the Northern Regional Research Laboratory in 1943 (14, 19). During the war years it was employed extensively for the production of starch for conversion into dextrose sugar, glucose syrup and industrial alcohol. The wheat gluten was used in the production of monosodium glutamate and as a source of high protein feeds. In this process flour and water are mixed to form a smooth, uniform, elastic batter. Additional water is then added to the batter under vigorous mixing. The starch is quickly released into the water and gluten is obtained as curds or small-to-large lumps. The gluten is separated from the starch and water on a mechanical screener. All of the starch water may be used directly for fermentations or converted into dextrose sugar or glucose syrup. Prime-quality starch may be recovered from the starch-water suspension by means of settling tables or centrifuges. Installations have been made on both a continuous and semi-batch basis. At the present time, existing operations are directed toward the production of fermentation alcohol and denatured gluten.

In addition to prime-quality starch, a lower grade, containing fiber and some protein, is obtained after separation of the high quality starch. The less pure product is used in pastes and adhesives, and in making cheap dextrins.

In processing wheat flour for starch production, a gluten product containing 75% to 85% protein is obtained. This is possible because 20% to 30% of dry-milled feeds, containing fiber and starch which would appear in wet-milled protein and feed fractions, have already been removed by the dry miller in producing the flour. Gum gluten may be obtained by drying in vacuum ovens or by recycling partially-dried gluten with wet gluten in a stream of hot air. Gum gluten is used in England and Australia to fortify flours of low protein content, and to improve the quality of flours having weak protein. In the United States it serves as an ingredient of gluten bread. Denatured wheat gluten is obtained when drying is carried out slowly at elevated temperatures. This type of product is a raw material for the manufacture of monosodium glutamate, a food flavor improver widely used in the Orient and rapidly coming into favor in the United States and other areas. Denatured gluten is also employed in mixed feeds and in water-emulsion paints.

Sorghum Starch from Flour. During World War II waxy sorghum starch was produced from sorghum flour (17) for use as a replacement for tapioca in foods. The flour was mixed with water adjusted to pH 6.8–7.5 to form a flowable slurry which was passed through a dispersion

mill to disperse the gluten gel to the sol state. The starch granules thus liberated were separated and recovered. This process is said to be applicable, with appropriate change of pH of the water used, to corn, wheat, rice and other cereal grains.

Alkali Process. Another method for the production of starch from wheat flour and other cereal flours was also developed during the war (**8**). This process, which was installed by one company on a commercial scale, is dependent upon the solubilization of the flour protein by dilute alkali. Starch is recovered by tabling or centrifuging the alkaline dispersion mixture, and protein is recovered by acidification of the starch-free protein dispersion in water.

Rice Starch from Milled Rice. Rice starch has been made from milled rice products obtained during the polishing of rice. Alkaline solutions are generally used to disperse the proteinaceous materials and thus free the starch granules (**11, 12**). The starch is washed, screened to remove fiber, separated by centrifugals and dried. The separation of rice starch is difficult because of the small size of the granules. Settling tanks are sometimes used in a step preceding centrifuging, but starch tables are never employed.

Industrial Production of the Starches

Data are not available on the present annual production of wheat, rice and sorghum starches in the United States because of the small number of manufacturers. The amount of each of the grains used for this purpose is doubtless considerably less than 1% of the total crop. At least three companies in the United States are producing wheat starch; one has in the past produced smaller amounts of rice starch; and two years ago one company started production of sorghum starch on a large scale. There is no industrial processing of barley, oats or rye for starch in the United States. Indeed, as far as is known, these three grains are nowhere used as industrial sources of starch.

Modified and Degraded Starches and Their Uses

Much starch is modified or degraded before use. Modified starches are produced by various methods and degrees of treatment, usually with acids or oxidizing agents. Often relatively little degradation of the starch is effected in a chemical sense. These starches find wide use in textile and paper-sizing and as adhesives. Pre-gelatinized starches which form pastes in cold water are made by gelatinizing the wet starch by heat or chemical agents and then drying it. Pre-gelatinized starches are used in drilling muds, in sizing paper pulp and in foods.

Partial degradation of dry starch by heat, acid or a combination of these, sometimes with other chemicals, produces dextrins. When heat alone is used as the dextrinizing agent, British gums are formed. Canary dextrins are produced by heating the dry starch with a small amount of acid, usually hydrochloric. When larger amounts of acid are used in dextrinization, white dextrins result; the excess acid in these products is often neutralized after the dextrinization is completed. Some dextrins are produced by enzyme action.

British gums and canary and white dextrins find use as adhesives, and paper and textile sizes.

Complete degradation of starch by treatment with acid yields glucose syrup from which the sugar, glucose, commonly called dextrose, can be crystallized. Two-thirds of the annual U. S. production of starch is converted into syrup and sugar. Both the syrup and the sugar find wide use in foods, and to a lesser degree are employed by other industries, for example, in making synthetic rubber, dyes, explosives and boiler compounds.

The syrup is used as an ingredient in such articles as inks, boot polish and hydraulic brake fluid. Dextrose sugar is employed in tanning leather, as a plasticizing agent, in hair-waving preparations, in explosives, in electroplating and galvanizing, and in many other processes and products.

A summary of the many uses of starch and starch products has been made by the Corn Industries Research Foundation (5).

Specific Uses of Starches from Small Grains

Because of comparative prices of the agricultural raw materials, relative efficiency of processing, and value of byproducts, starches from wheat, rice, barley, oats and rye, under normal conditions, could compete with the common starches of commerce only for specialty uses. In the United States, for example, corn starch generally constitutes about 95% to 98% of all starch produced. Potato starch occupies a similar position in some European countries.

Wheat starch is already employed in a number of fields. Wheat starch is said to be superior for laundry work and textile sizing because its small granules penetrate the fibers, while the large granules form a coating (9). Modified corn starches, however, compete successfully with wheat starch in the commercial laundry field. The ability of wheat starch paste to retain nearly its initial viscosity during hours of heating and stirring also makes it useful for warp sizing and textile finishing, as well as in textile printing pastes. A relatively minor amount of wheat starch finds application in adhesives in the form of canary and white dextrins and British gums. Wheat starch is also incorporated in some food products. Examples are salad dressings, in which it helps to stabilize the emulsion, and mixes, including some pie fillings.

Both wheat and rice starches are employed in cosmetics. The small size of rice starch granules makes this starch especially useful in face powders and textile sizings, and as an ingredient of laundry starches.

Oat starch has small granules, hence might find uses similar to those of rice starch. Barley and rye starches are somewhat like wheat starch in their paste characteristics. Further research would be required to determine their most promising fields of usefulness.

Since dextrose syrup and sugar can be produced by hydrolysis of any high-purity starch, the cheapest available starch is generally used for this purpose. It is probable that the starches under consideration, except sorghum starch, would be used for making these products only under relatively unusual economic conditions. For example, wheat starch was so used in the United States during World War II.

Dextrins differ, depending upon the starch from which they are made. Envelope dextrins, which have often been made from tapioca starch, were prepared from waxy corn starch during World War II. Waxy sorghum starch could presumably be used for this purpose, since it is similar to waxy corn starch. Starch adhesives for corrugated board have also been made from waxy corn starch, and again waxy sorghum starch would probably serve for this use.

The Outlook for Small Grains in Starch Production

Market prices and availability of small grains in relation to those of other starch-bearing commodities, comparative efficiency of processing and value of the byproducts are the chief factors which must be considered in evaluating the outlook for the use of these grains in starch production.

In the United States, for example, the grains under consideration, with the ex-

ception of sorghum, usually command a higher price per bushel than corn. The recent erection of a starch plant with a rated capacity of 20,000 bushels per day in a sorghum-growing area (10) has initiated the production of sorghum starch in this country. It is too soon to predict how successful the competition of sorghum starch with corn starch will be.

Efficient and economical production of starch depends upon the operation of a factory of optimum size. Corn starch manufacturers usually strive for a daily grind of at least 20,000 bushels. Below this rate of production, manpower is not used to the best advantage, since one man can control several units of specialized equipment in the same time that he would spend in controlling only one unit. In addition, there is a low margin of profit on starch, and a large volume of production is necessary to provide adequate earnings.

An efficient and successful starch factory must have adequate and profitable outlets for its byproducts. The cornstarch industry of the United States, for example, could not operate without its sales of feed and oil. For example, about 1.6 pounds of oil are recovered from each bushel of corn processed; the value of the oil is estimated to cover much of the cost of processing.

Wheat starch is produced profitably because it meets specialty demands and because the gluten which is concurrently produced finds a ready and profitable market. This does not mean, however, that additional large wheat starch factories would be profitable. A recent survey was made to determine the practicability of erecting one or more plants in the northwestern United States to produce starch, dextrose syrup and glucose from wheat grown in that area (3). It was concluded that "wheat must be available to users at a price, pound for pound, no greater than the price of corn in the Corn Belt".

TABLE IV

STARCH CONTENT OF COMMERCIAL WHEAT, SORGHUM, RICE, BARLEY, OATS AND RYE, IN COMPARISON WITH THAT OF CORN

Grain	Weight per bushel	Starch content as purchased[1]	
	Pounds	*Percent*	*Pounds moisture-free starch per bushel*
Wheat	60	56	34
Sorghum	56	62	35
Rice (rough)	45	53	24
Barley	48	49	24
Oats	32	36	12
Rye	56	52	29
Corn (shelled)	56	63	35

[1] Calculated for grain with 13.5 percent moisture.

The demand for rice starch for specialty uses is so small that production is uneconomical, partly from the standpoint of labor costs involved and partly because the byproducts cannot profitably be saved when production is on such a small scale.

Methods have not been established for the efficient separation of starch from barley, oats and rye. Another present deterrent to the use of these grains for starch production is the lack of byproducts of known value and use. The value

of oil from barley, oats and rye is as yet unknown; and the recovery of germ, from which the oil is obtained, is impracticable in processing these grains by existing methods.

Necessity for the profitable sale of the byproducts of starch separation from the six grains under consideration is further emphasized by the fact that most of these grains contain less starch, as purchased, than corn, with which they must compete (Table IV).

It is conceivable that wheat, sorghum and rice may be more widely used for starch production and that starch may be made commercially from barley, oats and rye. A thorough understanding of the technical and economic problems involved will, however, be required as a basis for the successful operation of a starch factory using one or more of these grains as raw material.

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Production and Utilization of Sugar Beets[1]

Processing of sugar beets has become a major chemical industry in the United States. About one-quarter of the country's sugar requirement is obtained from about 12 million tons of beets grown on 700 thousand acres of land. This industry has succeeded through the combined efforts of scientists in many fields, who have improved resistance to diseases, sugar content of beets, methods of farming and processing procedures. Feed pulp, molasses, glutamic acid, potassium salts and betaine are by-products of the industry.

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Production of sugar beets has expanded in less than 200 years from insignificance to a prominent agricultural industry. Once grown as a forage crop, sugar beets now supply sucrose in human diets throughout the temperate zone of Europe and North America. Unlike most agricultural processing industries, this one did not arise from an art or craft passed on by many generations, but developed directly from the laboratory. While it is true that farmers in Silesia, Germany, prepared table sirup from beets, and also that Indians of the Santa Clara Valley in California made sugar-rich foods from vegetables which might have been sugar beets (13)[3], in neither case was the enterprise expanded beyond a family scale.

The laboratory discovery that marks the beginning of the sugar beet industry was made in 1747 by Marggraff (28) who isolated sucrose from beets. Practical application of this discovery was made in 1797 when Achard (1) constructed a small factory in Cunern, Germany, for sugar production. Although this enterprise and a subsequent one by von Koppy failed, the two men realized that selection and breeding of sugar-rich beets was essential to survival of the industry. Von Koppy's work on selection of strains of beets led to the discovery of the White Silesian beet that has earned the title of " mother stock of all the sugar beets in the world " (24).

Considerable impetus was given to work on beets by Napoleon's decree in 1811 that ordered increased production of beets and subsidization of factories to make France independent of British colonies for sugar. Following work instituted in those years, Louis de Vilmorin enunciated the principle that the breeding value of the mother plant is determined by the quality and character of its progeny. He also developed the polariscopic method for following the change in sugar content of beets. It is interesting to note that as early as 1861 he had grown beets containing 16 to 17 percent sucrose, a concentration com-

[1] Report of a study made under the Research and Marketing Act of 1946.

[2] Bureau of Agricultural and Industrial Chemistry, Agricultural Research Administration, U. S. Department of Agriculture.

[3] The literature on sugar beets is so extensive that a complete bibliography is practically impossible. The references cited will provide the reader with additional information and citations. Recent general references on sugar are given in Refs. 18 and 38.

paring favorably with average value of beets grown at present (9).

Breeding [4]

Selection and breeding of sugar beets to increase sugar content has continued extensively from the time of Achard to the present. The method commonly employed is based on Vilmorin's principle and usually requires eight to ten years between choice of mother plant and commercial production of seed. The mother plant is selected on the basis of morphology and sugar content. Seed is then selected from those which are the best seed producers. A test of the progeny is made and the poorer ones are eliminated. The better performers are grown on larger plots for production of roots (stecklings) and selection of best performers. The progenies are then field tested, and in some cases the best performers are crossed again. Testing is usually continued for two or more years before the seed is sent out for commercial production.

This method has proved satisfactory for increasing yield, resistance to diseases such as curly-top, *Cercospora* leaf spot and black rot, and resistance to bolting.

Most of the seed used in this country prior to 1937 was grown in Europe, where labor costs were low. The biennial beet requires that the stecklings be removed from the ground for protection against freezing. They are then replanted in the spring for seed production in the fall. Labor costs of this method are high, as is loss of beets through fungal attack. Seed producers were at a further disadvantage in the development of varieties resistant to curly-top and to *Cercospora* leaf spot because such diseases hardly exist in Europe.

A valuable contribution was made by Overpeck (29) when he observed that sugar beets planted in August or September in southern New Mexico would bear seed the following summer. The exact temperature that shocks the plant into fruiting is still unknown, but a temperature as low as $-6°$ F. is tolerated by the beet, provided it is not maintained too long. The observation meant that machine methods could be used to plant beets and harvest the seed, thus reducing costs. One year is saved in the production of seed and the testing of crosses. This new crop, having a value between two and three million dollars per year, has increased farm income of the United States. Attempts at vernalization of beet seed have been made, but the results have not been promising.

Economical production of sugar beet seed in this country gave new impetus to the breeding program which has been continued somewhat along the classical lines of Vilmorin. The program has been particularly important to the industry west of the Rocky Mountains. In this region a beet-leaf hopper carries a virus which causes development of curled leaves. The beet containing virus is prey to other infestations and soon dies. At one time the destruction of sugar beets by curly-top was so great in Idaho, parts of California, Washington and some other localities that factories had to be closed. In some cases the factories were dismantled. Yields dropped, from ten tons or more per acre, so low that fields were plowed under. Some progress was made by planting seed as early as possible so that healthy older plants were developed before the hopper invaded the fields. A better control was obtained when Carsner and Pack in 1929 (8) announced development of a variety (U. S. No. 1) that was fairly resistant to curly-top. The variety has since been improved, and most of the curly-top-resistant varieties are those bred by the Bureau of Plant Industry, Soils, and Agricultural Engineering, U. S. Depart-

[4] Much of the information for this section has been drawn from Ref. 9.

ment of Agriculture. The sugar-beet industry is now thriving in the areas that were blighted only 20 years ago. In Washington a factory has been rebuilt on the site once considered unprofitable because of curly-top virus. Success of the research program against curly-top is well illustrated by the 1950 campaign in California. The virus destroyed 50 percent of the tomato and honeydew melon crop. Planting of beet variety U. S. No. 22 with subsequent crop spraying reduced loss of sugar beets to 2.5 percent.

The work described was accomplished by crossing of strains resistant to the disease, but a different approach to the breeding of such beets is possible. Savitsky (10) postulates that sucrose production is governed by four genetic factors, three of which exist in beets and the fourth in Swiss chard (both *Beta vulgaris* L.). Genetic factors of importance are also obtained from wild sugar beets. Recently plants of the variety *Beta maritima* Milpitas, found growing wild in California, were crossed with a commercial variety to increase resistance to *Cercospora* leaf spot (14). This resistance has been achieved, although back crossing has been necessary to eliminate bolting, caused by the fact that the wild beet is an annual type.

More recently a new approach was made possible by the discovery of lines of self-fertile beets and beets which produce no pollen. The male-sterile beets can be fertilized by the self-fertile to produce pedigreed hybrids. Only a beginning has been made in the study of pedigreed hybrids, but results appear promising. One type, resistant to curly-top, and lines showing low-bolting tendency have already appeared.

Another problem that might be solved by the use of selfing beets is the production of single-seeded or unilocular fruits instead of the multiple-segmented seed ball. Savitsky (32) has reported obtaining five monogerm self-fertile sugar beet plants in a field of 300,000 plants of "Michigan Hybrid 18" and none from curly-top-resistant types. Progenies from two of the five plants showed characteristics of true monogerm plants. These two progenies have been planted and crossed with curly-top-resistant varieties in the hope that elite seed will be available on a large scale in 1952 or 1953.

Production

Sugar beets are grown in all parts of the North Temperate zone. Spain, where sugar beets and sugar cane are grown together, Asia Minor and the Imperial Valley in California represent the southern limit for beets, while Canada and Sweden are in the northern limit. The main climatic requirements for beet growth for sucrose production are rain or other frequent application of water during the growing season, mean temperatures near 70° F., and cool dry weather at the end of the season (6). In California water is withheld from beets near the end of the season, which is in May and June in Imperial Valley, and the sucrose content remains high despite the hot weather at that time.

Although sugar beets were introduced into Massachusetts in 1838, it was not until 1870 that the first successful factory was established in the United States—on the opposite side of the country in Alvarado, California. That factory is still in operation, with some revisions and modernization of equipment. There are now in the United States over 80 factories distributed in the West and Middle West. California, Colorado, Idaho, Montana, Nebraska and Michigan are the leading States in processing sugar beets.

Yields of sugar beets per acre in the United States have increased from an average of 10.1 tons in 1914–1918 to 13.6 tons in 1945–1949. In 1949 California

FIG. 1. The silver sugar beet flourishes in the Great Lakes region, the Rocky Mountain States, California, southern Canada and the Pacific Northwest. Sugar is produced in the green leaves of all plants, but by careful crossbreeding the sugar content in the long tap root has been increased so that an acre of beets produces approximately the same yield as an acre of sugar cane.

had the highest average yield, which was 18.8 tons per acre with small areas yielding as much as 52 tons, while Michigan had the lowest, 9.6 tons per acre. The prices paid to farmers in 1948 averaged $10.40 per ton, not including program payments which were $2.45 per ton. The average return to the farmer was $141 per acre without program payment and $175 with it. In the United States the growers of sugar cane obtained $121 per acre of cane grown and $146 per acre, including payments under Federal sugar program. The yield of sugar per acre of beets is slightly higher in the United States than the yield per acre of cane.

The smallest factory considered economically feasible would process 300 tons of beets per day (40). Since the operating season is usually about three months, at least 27,000 tons of beets would be required. In actual practice the smallest factory in this country processes about 1,000 tons a day and requires nearly 100,000 tons of beets. The sugar beet company either has to have considerable land available or must obtain contracts from local farmers to assure a sufficient supply of beets. As a result the companies have become complex organizations, contracting for land, supplying seed and fertilizer, and giving other assistance to the farmers under contract.

About one-third of the sugar in the world is obtained from sugar beets (Table I). Most of the sucrose requirements of Europe and Russia are met by

TABLE I

SUGAR BEETS: AREA, YIELD, PRODUCTION[a,b]

Country	Area in 1,000 acres			Production in 1,000 tons			Sugar in 1,000 tons		
	1935-39	1945	1948[c]	1935-39	1945	1948	1935-39	1945	1948
Europe									
Austria	105	22	54	1,234	112	397	196	20	58
Belgium	122	94	112	1,731	998	1,673	259	156	295
Czeckoslovakia	380[d]	372[d]	421[d]	4,441	3,006	4,920	721	494	697
Denmark	99	96	108	1,595	1,422	1,886	257	189	291
France	579	488	724	7,165	4,927	10,473	1,059	508	1,061
Germany	1,071	493[d]	857[d]	14,179	5,512	10,164	2,122	860	1,437
Italy	273	71	279	3,135	443	3,758	416	21	502
Netherlands	107	45	116	1,759	495	2,086	257	66	311
Poland	331[d]	457[d]	518[d]	3,147[d]	3,059[d]	4,658[d]	548	216	765
Rumania	100	106	151	842[d]	243[d]	680[d]	129	31	125
Spain	193	144	247	1,221	1,067	1,819	209	132	288
Sweden	128	135	116	2,089	2,000	1,993	340	309	321
United Kingdom	346	417	413	3,399	4,353	4,599	527	603	679
Total Europe	4,091	3,214	4,650	48,461	29,462	53,221	7,410	3,822	7,419
U.S.S.R.	3,023	2,029	2,842	18,651	9,557	16,865	2,887	1,200	2,000
North America									
United States	828	713	694	9,623	8,626	9,422	1,518	1,266	1,369
Grand Total	8,061	6,144	8,364	77,674	48,873	81,001	12,025	6,575	11,094
Grand Total Beet and Cane Sugar							34,707	26,232	37,274

[a] "Yearbook of Food and Agricultural Statistics for 1948," United Nations, Washington, D. C.
[b] "Agricultural Statistics 1949," U.S.D.A., Washington, D. C.
[c] Bulgaria, Eire, Finland, Hungary, Switzerland, Yugoslavia, Canada, Mexico, and Turkey harvested less than 100,000 acres. Their acreage and production are included in the totals.
[d] Figures not comparable because of boundary changes.

beets. In Europe, only the United Kingdom, with its extensive colonial empire and naval power, imports large quantities of raw sugar made from sugar cane. The course of history of sugar beets has therefore been dependent not only on climate but also upon freedom of the seas.

Farming Practice

Sugar beets produce a segmented seed ball, each segment containing a seed capable of producing a plant. Since seed balls rather than separate seeds have been planted, thinning of planted fields has been required to reduce the population to one plant for about 200 square inches of soil area, which gives maximum sugar production. Thinning has always been a tedious and expensive hand operation, and efforts to mechanize it have continued for a number of years. Planting machines have been designed to plant uniform seed rows. Later, screening has been adopted to obtain only small seed balls containing one or two seeds. More recently grinding machinery has been used to break down the seed ball to produce segments with fewer germs.

At the same time there has been a gradual change in opinion on the optimum number of plants in a hill. In the past, one plant was considered the most desirable, but now two plants and even three are not believed to be harmful to sugar yields. This change, coupled with the development of segmented or decorticated seed, caused an increase in the acreage planted and thinned mechanically in the United States from a fraction of one percent before the war to over 50 percent at the present time.

Uniform planting of single seeds has simplified mechanization of weeding, thus reducing another portion of operating expense.

Harvesting used to be done by hand labor. Now several machines have been constructed which pick up beets by the tops, on spikes or some other way, cut off the tops, screen off the lumps of soil, convey the beets to loaders and pile the tops in windrows. Reduction in harvesting cost has been considerable. Factory costs have probably increased a little, inasmuch as more of the crown is left on machine-topped beets. The crown usually is richer in invert sugar and other impurities which affect processing. The advantages gained, however, are so significant that most beets are now harvested mechanically.

The improvements mentioned have placed the beet industry in a better competitive position with respect to cane. Land, water and processing costs still favor cane, but as standard of living increases in cane-growing areas, even this disparity may be reduced.

Manufacture

Although Marggraff isolated sugar from beets in 1747, the first factory was not constructed until 1797 when the King of Prussia subsidized Achard. The latter, not knowing the chemical properties of sucrose, used acid in one purification step, thus causing inversion of a fair percentage of sucrose. Only one of his steps, the coagulation of proteins by heat, remains in general use. Others, such as addition of milk and egg whites as clarifiers, have been discontinued in the United States. Powdered skim milk is occasionally used as a clarifier in European factories.

Fundamentally beet sugar manufacture is based upon three operations: (*a*) diffusion, (*b*) purification of the diffusion juice, and (*c*) fractional crystallization of the sucrose. The steps will be discussed in order with mention of the necessary working operations. Additional operations for the treatment of molasses will be discussed separately. The steps are based on practice in America, although differences occurring

in Europe will be given when they are known to us.

Preliminary to factory operations beets are trucked or shipped in from the fields. Usually the haul is less than 100 miles, but in some cases the shipping distance is as much as 400 miles. The beets are stored in huge piles arranged to permit maximum ventilation (7, 22). The latter serves two purposes: to admit cool night air throughout the pile, thus decreasing respiration and loss of sucrose, and to remove vapor resulting from respiration. Water loss from respiration also has a cooling effect. In recent years forced ventilation at night has been used to reduce the temperatures in the storage piles. In Imperial Valley, where temperatures above 90° F. are common during the harvesting season, sheds are provided to deflect the sun's rays from the beets. In other localities whitewashing (23) the outer layer of the pile has been used for the same purpose. By these techniques a saving of 0.1 percent or more of sugar can be made for every 24 hours. This appears to be a small saving, but the sugar industry operates on a very narrow margin and even a small saving multiplied by several million pounds becomes a significant factor. On long-continued storage, especially if the beets are frozen, then thawed, the percentage of sugar decreases below an economical value, and decomposition of the beets decreases the purity of the beet juice.

Beets are moved from storage piles or trucks by conveyor belts or flumes. They are washed to remove leaves, dirt, rocks and other trash. The water is usually recycled, but in some factories in Europe the dirt and rocks are removed by sedimentation, some of the organic impurities are destroyed with hypochlorite, and the water is used in diffusion batteries.

The cleaned beets are conveyed to a slicing machine with rotary knives. In America the knives are about 166 mm. wide and subtend an edge angle of 82° The height of the knife is about 1.75 to 2.25 mm. European practice is to produce a thicker slice (cossette or noodle), 2.75 to 3.25 mm. (41). The slicing rate ranges to about 30 ft. per second with a single cutting machine handling up to 125 tons of beets per hour. Slicing increases the surface area for diffusion, thus reducing diffusion time. Too thin a slice is likely to decrease the purity of the juice and adversely influence the pressing characteristics of the pulp.

Diffusion. The first major problem of the factory operation is removal of sugar solution from beets. In the cane industry alternate pressing and washing are used, but the beet does not have a sufficiently fibrous structure for application of such presses, although preliminary pressing is used in some factories in Europe. In the United States sucrose is diffused from the cossettes. The ideal situation would be diffusion of nothing but sucrose into added water and retention of all the impurities in the pulp. This appears to be the secondary goal, the primary one being complete removal of sugar, even though subsequent purification costs might be increased. A compromise on size of cossettes has to be made. The number of beet cells ruptured will control the amount of colloidal impurities liberated; thus the surface area cannot be increased to a maximum. The amount of water used must be controlled because it is removed later. Time is pressing, because stored beets deteriorate. During operation of the factory, constant adjustments of water and rate of cutting are made to obtain maximum yields of sugar in minimum time.

The diffusion process has grown around a series of cells called batteries. Each cell is capable of holding five or six tons of beets. Beet cossettes and then liquid are introduced at the top. Often 12 to 21 cells are arranged in a circle with water going countercurrently from the exhausted pulp to the fresh cossettes. The temperature is at a maximum of

FIG. 2. Yielding over a million tons of refined sugar annually, sugar beet culture is an important part of the agricultural economy of 19 States. Recent mechanization has eliminated much of the hand labor formerly connected with this crop.

about 80° C. near the cossette part of the cycle and decreases to 50 or 55° C. at the pulp end. In Europe even higher temperatures are used in the first cell, or the beets are given a steam blanch. It is believed that the enzymes and other proteins are immediately denatured, the resulting sugar solution is purer and that diffusion is more rapid from dead than from living tissue. In addition, high temperatures must be maintained to sterilize the diffusion juice.

The ratio of weight of extract to weight of beets multiplied by 100 is called the "draft" and is maintained at about 120 in Europe but closer to 140 in the United States. The latter value permits greater extraction of sugar but appears to increase the concentration of non-sucrose materials.

The batteries are large installations, cumbersome to operate, and require several laborers. They are intermittent in operation and produce a pulsing flow of juice into the purification step. Also channeling can occur, which decreases the extraction of sugar. Considering these factors it is surprising that other types of equipment were not fully developed earlier. Only in the past ten years have successful continuous batteries been tested on a factory scale in this country. In Europe several continuous diffusers have been in use, some for over 20 years. Of these the Rapid, Philipp, Berge (3), Tirlemont (36), Olier (41), Hildebrandt (2), Harburg, and Schladen have been recently described (20). The Hildebrandt is interesting because to save floor space it is constructed in the form of a U. The fresh cossettes travel down one side, across, then up the other side. The drive mechanism is a helical screw with a long pitch which is decreased at the cossette outlet in order to obtain pressing action. The screw has shielded perforations to allow liquid to go countercurrently to the cossettes. In the United States two diffusers, the Silver-Chinook (34) and the Oliver-Morton (26), operate both countercurrently and concurrently. There are 19 to 23 cells in these batteries. Water enters at one end; the beet cossettes move countercurrently with respect to the battery. In the cells of the Chinook and Oliver-Morton the cossettes and liquid move concurrently through the action of a scroll. The cossettes and liquid are separated by a suitable device so that the cossettes travel one way, the liquid the other. The original Silver battery has trays on a chain drive to hold the cossettes and carry them countercurrently through the cells. It is noteworthy that they permit a decrease in draft down to 110–125. They thereby increase the capacity of the evaporator station of the factory by 10 to 20 percent. In actual practice the increase is greater because of the continuous nature of their operations. There is a marked reduction in the labor force required to operate a continuous battery compared to that for the batch battery (12).

For every ton of beets there will be 1.1 to 1.5 tons of diffusion juice. It will contain 12 to 14 percent sugar and about one percent of non-sugar materials (a purity of about 85). The impurities are primarily sodium and potassium salts of chloride, sulfate, phosphate, betainate and citrate, with a variety of amino acids, of which aspartic acid and glutamic acid with its amide predominate. Depending upon the region in which the beets are grown, there are also significant quantities of oxalate, lactate and malate. About 0.1 percent of colloidal material, pectins, other polysaccharides and proteins are also present, and they prove troublesome in later operations.

Purification. The purification step is required to remove the colloidal matter to reduce filtration difficulties. It should also remove as many other impurities as possible. The number of reagents that have been tried for this purpose is legion,

and of them all lime and carbon dioxide have proved the most practical (25).

Lime provides alkalinity to deesterify pectin and calcium ions to precipitate it. The calcium ion also precipitates oxalates, citrates and phosphates. The added carbon dioxide removes excess calcium in the form of carbonate which at the rate of 1.5 to 3 percent of beets, is introduced at the top of the container. Carbon dioxide is introduced at the bottom to keep the pH from 10.7 to 11. The alkalinity (35) and ionization of the calcium salts (17) are the important points; hence titrations rather than pH measurements are used for control. The

FIG. 3. New agricultural implements, like the harvester shown here, have taken over much of the hand labor formerly connected with getting in our hundred million dollar beet sugar crop.

acts as a settling and filter aid. The tremendous surface area available for adsorption of various impurities must also be a factor in this step.

The liming and so-called first carbonation are carried out continuously in most factories. Diffusion juice above 90° C. is forced into a cylindrical container to cause vigorous mixing. Lime, lime is maintained at 0.069 to 0.083 g. CaO to 100 ml. of juice to obtain optimum results. An electrode system sensitive to changes in hydroxyl ion concentration would offer possible improvement in this operation. Time of reaction is also an important factor, since the calcium carbonate nuclei must become sufficiently large to settle rapidly. The

treated juice is usually sent to a settling chamber, then to filters, reheated to around 90° C. and treated again with CO_2 to reduce the pH to 8.5 to 9.2. Supersaturation of calcium carbonate must be prevented at this stage or scaling will occur in heat-exchange equipment. Therefore time again becomes an important factor. The latest attempt to control alkalinity and supersaturation is a compartmentalized carbonator, in each section of which CO_2 is added. This allows some nuclei to form, provides continuous and thorough agitation, and gives them a chance to grow to reasonable size, which aids in the following filtration step and decreases the chance for supersaturation (5, 31).

Sulfur dioxide is added to react with reducing sugars and prevent browning reactions It is added at a ratio of about 0.5 lb. of sulfur per ton of beets and causes a drop in pH to about 8. Decolorization is obtained in some factories with activated carbons. The treatment has not received the same degree of acceptance in the sugar beet as in the cane industry. The juice at this point, called thin juice, has a purity of about 91.

Crystallization. The operations described so far are all that are used for purification. The next step is to increase the sucrose concentration to the level required for crystallization. Multiple-effect evaporators are used and produce what is called " thick " juice. The concentration of sugar is increased from 13 percent to about 60 percent in an evaporation time of a few minutes. This is then proportioned with washes from the first centrifuges and with intermediate and raw sugar to make a standard liquor with a purity near 92. The standard liquor is treated in some factories with SO_2 and then filtered to produce a sparkling clear sirup.

The standard liquor is further concentrated in vacuum pans. The operation of these pans is under the control of the sugar boiler who closely watches the evaporators to introduce sucrose nuclei at the optimum moment to induce uniform crystallization. The operation requires nice judgment, involving either more boiling or introduction of more liquor to maintain uniform crystal growth. In the first pan, crystallization is usually complete in a short time. The massecuite is then centrifuged, and the white sugar is washed and sent to driers, screens and packagers, or to storage.

The mother liquor goes to the second, intermediate or high raw pan where a second less-pure crop of crystals is obtained. These are sent back for recrystallization in the first pan, while the mother liquor goes to the third or low raw pan. Impurities have now accumulated about six-fold, reducing the rate of crystallization considerably. Usually a day or more is required for the crystallization to reach a reasonable value. A crystallizer is used at this stage to increase the amount of sugar crystallized.

From this stage low-raw sugar is obtained, which is returned to the standard liquor. In many factories where the sulfate content of the low-raw is high, the sugar is recycled through the defecation operation where calcium ion precipitates some of the sulfate. The mother liquor is molasses which contains less than 50 percent sugar with a purity of about 60. About 85 to 89 percent of the sugar is recovered in this straight-house operation.

Steffens Process. Molasses contains about ten percent of the sugar originally present in the beets. In Europe the sugar is used for fermentations or animal feed. In this country the disparity in price of sucrose compared to its price in molasses has caused considerable effort to recover sucrose from molasses. Steffens, in Germany, devised a method based on the insolubility of calcium sucrate. The method was not successful in Europe because dilution of the molasses required to obtain quantitative

recovery of sucrose increased the fuel costs so much that the economics of the process were unfavorable. There were additional equipment problems in grinding the lime to obtain as great a surface area as possible and to separate the sludge after its formation. These problems have been fairly well solved, and of the 80 sugar factories in the United States, 26 have Steffens houses. In 1946, of the 73 million gallons of beet molasses formed, about 36 million gallons were Steffenized.

For this operation molasses from the "home" factory and from other nearby straight-house factories is treated. It is diluted to ten percent refractometric dry solids (R.D.S.) or less because removal of sucrose is more quantitative at low concentrations. It is then cooled to about 15° C. and calcium oxide is added either continuously or batch-wise to produce a calcium sucrate. The precipitate is filtered, the temperature of the mother liquor is increased to 80° C., and more calcium sucrate precipitated. The mother liquor, which is almost free of sugar under optimum conditions, is a waste and will be discussed later.

The calcium sucrates are returned to the liming tower, where they replace some of the lime. Lime consumption in a Steffens plant is almost double that of a non-Steffens plant.

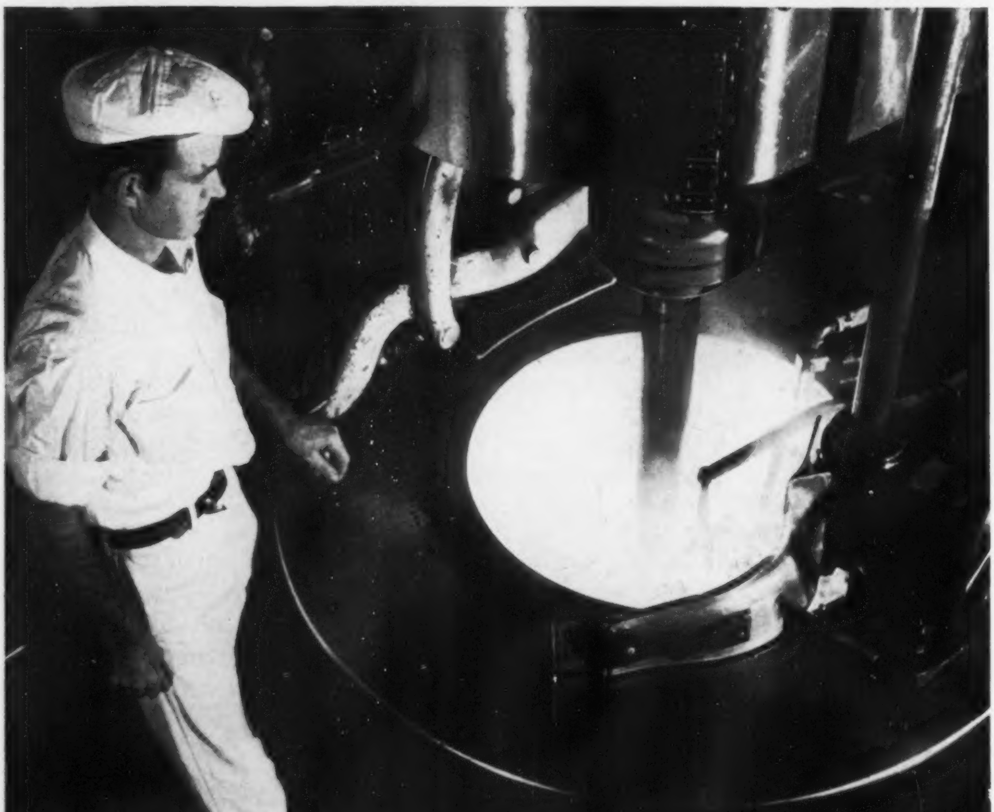
Mature beets ordinarily contain a small amount of raffinose. This sugar precipitates with lime along with certain organic anions, and as they recycle with sucrose in the factory they increase in concentration. The percentage of non-sucrose compounds eventually increases to a point that causes them to interfere with effective operation of the Steffens process. The sugar-rich liquor is called "discard" molasses and contains about 50 percent sucrose with a purity of about 60. The recovery of sugar at this point is 92 or 93 percent, although with optimum treatment recovery could be higher (33). One factory in California where raffinose is not a problem recovered 97 percent of the sucrose (42) over a five-year period, a recovery equaling the best reported by ion exchange (21).

Barium Process. More sucrose can be removed by use of barium hydroxide which forms a less soluble sucrate than lime. The operation can be carried out at high concentrations of sucrose, thus reducing fuel costs and making the recovery of byproducts more economical. The cost of barium ore is higher than that of limestone and its conversion to the oxide is also expensive, so that barium must be recovered. As a result there are only a few barium plants in the world, one of the largest being in Johnstown, Colorado (15).

At the latter, discard molasses is shipped in from several nearby plants and treated with barium hydroxide. The precipitate is filtered and carbonated to form barium carbonate and leave sucrose and raffinose in solution. The filtrate is concentrated to recover potassium salts. The remaining liquor is concentrated for feed supplement. The sugar solution is evaporated and the sugar crystallized. The operation is continuous until the raffinose interferes excessively, when a discard molasses is formed.

The overall recovery of sugar is about 95 percent. It is noteworthy that no trace of barium remains in this sugar. Its crystal shape is longer than ordinary, probably because of the effect of raffinose on sucrose crystallization.

Ion Exchange Treatment. The success achieved by ion exchange materials in softening water presaged a useful career in sugar purification. The discovery that phenols and amines polymerized with aldehydes could act as cation and anion exchangers opened the way for the development of high-capacity, stable and cheap exchangers. The first two of these goals required by the sugar industry have been practically achieved,



but further progress must be made on the third. Besides the investment costs, chemicals used for regeneration of the resins, equipment and controls add to the expense so that managers of factories already containing defecation equipment are reluctant to change. Less than ten years after resin exchangers had been developed, Vallez (39) was applying them to sugar-juice purification in a factory at Mt. Pleasant, Michigan. Since then, pilot plants have been erected at a number of factories, and at least three factories are equipped to refine their full capacity with resins.

Development in this field is so rapid that description of plants now using resins would probably be of only historical interest in another few years (19). There are a number of stations in the sugar factory at which ion exchangers could conceivably be introduced: after diffusion; after second carbonation or sulfitation, if used; after the second or the third pans. All introductions have been considered and some are still under examination.

Liming and first carbonation is an economical way of filtering juice and removing some of the impurities that would exhaust or plug an exchanger; therefore most installations introduce the resins after defecation. In one factory attempts are underway to treat diffusion juice with only 0.5 percent or less of lime to remove the colloidal matter (30). At other factories low-raw sirup or molasses is treated (4).

The treatment is essentially the same in all factories. The sugar solution is adjusted to a concentration in the range of ten to 30 percent, depending on whether thin juice or machine sirups are used, and cooled in heat exchangers or vacuum evaporators to a temperature below 20° C. Low temperatures are necessary to decrease the rate of inversion of sucrose, although the new single-bed treatment if successfully applied to processing liquors will eliminate this problem. The cooled liquor is allowed to flow over the cation exchanger in the hydrogen form. The cations are removed from the liquor and replaced by hydrogen ions. The drop in pH from about 8 to 2 explains the tendency to form invert sugar in this chamber. This tendency is greater than indicated by the pH because of the excess of hydronium ions in the neighborhood of the resin surfaces compared to the bulk of the solution where the pH measurement is made. If a large supply of cool water or vacuum cooling equipment is unavailable, use of resins in sugar work will be impossible because of inversion unless the new one-bed treatment used in water-softening can be applied. When the pH of the effluent solution reaches 5, the resin bed is considered exhausted. Even at that pH many amino acids and other weak bases go through with the sugar. The effluent is then passed through an anion exchanger until the pH drops to 7–7.2. At this pH many weak acids leak through the resin so that the impurities of the sugar solution are not entirely non-ionic. The sugar solution has a purity of 95 and is boiled down in regular equipment. The resin beds are washed and the sugar-rich wash solution sent on through the process. After washing, the regeneration is accomplished with ammonia or sulfuric acid solution, depending on the ionic character of the resin. Usually the capacities of the resins decrease, so that occasionally the cation exchanger is treated with base to remove additional impurities before it is regenerated with acid. Similarly the

FIG. 4 (*Upper*). In the factory, beets are sliced into cossettes and soaked in hot water to remove their sugar content. This is a typical installation of a Robert battery.

FIG. 5 (*Lower*). In high speed centrifuges the thickened sugar juice from the vacuum pans is whirled at speeds up to two miles a minute to separate the sugar crystals from the molasses.

anion exchanger is given an acid treatment before regeneration with ammonia or soda ash.

Resins have been used for years in one or two factories, and the attrition losses of resins are very low. Most of the excess ammonia used during regeneration can be recovered by distillation from lime (11). No use has been found for the sulfuric acid unless it is reacted with some of the ammonia to make ammonium sulfate, useful as fertilizer (19). There are some gains from use of resins. Evaporator scale formation is markedly reduced. The rate of crystallization is increased, which might be a disadvantage until operators become used to it. The fuel bill is decreased, since smaller quantities of mother liquors are recycled back through the process. More sugar is recovered, up to 96–97 percent, but there is a loss of molasses which must be considered. Several have reported an overall decrease in costs with resins, compared to straight-house operation (see for example Ref. 19). Comparisons with Steffens treatment have been made only in Europe (37). The latter study indicates that lime or strontium is cheaper than ion exchange treatment.

The sugar boiling system has been simplified by the one company operating its entire output through resins. Only two pans are used, with recycling from the second as impurities increase. Sucrose from the second pan is slightly off-color but salable. Further improvements in the application of ion exchangers to purify sugar solutions are expected as experience is gained.

Utilization

Sugar. Consumption of cane and beet sugar in the United States reached 7.5 million tons in 1948, compared to an average of 6.7 million tons from 1935 to 1939. On a per-capita basis the 1948 consumption was 103 lbs., while the peak was reached in 1926 at 115.8 lbs.

The pattern of sugar consumption has gradually changed. Industrial uses in 1946 accounted for over 50 percent of total consumption, whereas in 1939 they accounted for only 34 percent. This increase is attributed to the growing tendency of consumers to buy more baked, canned, frozen and other prepared foods.

This change in pattern presages another change in the method of marketing sugar. In the past practically all sugar was sold in crystalline form. Industrial users then redissolved it before addition to the products being processed. Now liquid sirup is sold by sugar processors to nearby utilizers. This saves some fuel costs and represents a form of sugar that can be readily stored and transported with a minimum of labor. Industry is also supplied with a variety of particle sizes ranging from confectioners powdered sugar to the usual coarse-grained product. Recently brown sugar has been added to the sales lines of many sugar beet companies. This requires some inversion and addition of flavoring material to make a product satisfactory to consumers.

Attempts to make derivatives of sugar that would have industrial possibilities have been frequent and somewhat disillusioning. Sugar octa-acetate has been made on a small scale, but the market was readily saturated. Allyl sucrose has possibilities as a lacquer but would have to compete with similar products. Levulinic acid and furfural derivatives have promise, but sucrose, at present prices, cannot compete with glucose as a raw material. Derivative uses of sucrose do not appear to offer a significant outlet in the foreseeable future.

Byproducts — PULP. The wet pulp from the diffusers usually is given a pressing in a screw press to reduce the water from about 90 to 80 percent. In Europe the press water is reused in the batteries after hypochlorite oxidation. The press water has a fairly high bio-

chemical oxygen demand, and disposal in sewer systems will undoubtedly be curtailed in this country. The pressed pulp is either sold directly to the farmer for feed, siloed or dried in rotary kilns, sacked and sold as feed. Prior to drying, molasses (about 25 percent of the weight of dry pulp) is usually added. At current market prices this practice assures about $40 per ton for the molasses, or about three cents per pound for the sugar in the molasses. The 1948 production was 1,346,000 tons of moist pulp, 76,000 tons of dried pulp, and 207,000 tons of molasses pulp.

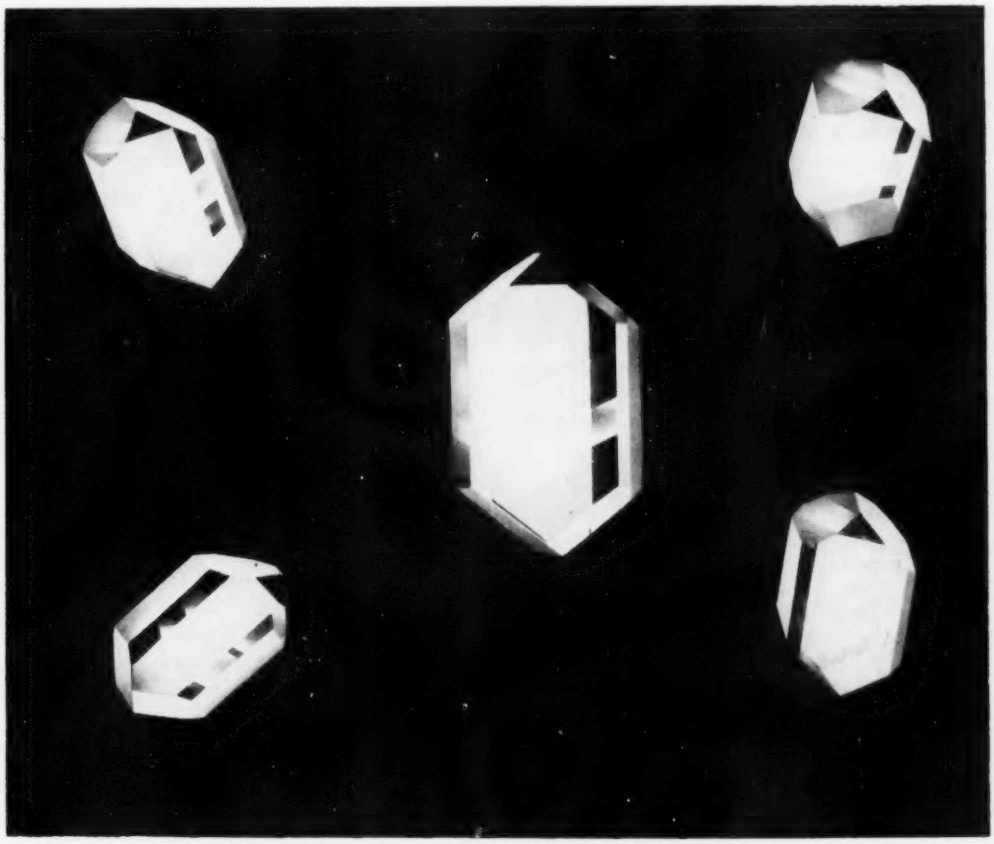


FIG. 6. Crystals of pure sucrose.

MOLASSES. One outlet for molasses has been mentioned. Beet molasses contains a variety of organic compounds that are necessary for growth of microorganisms and is fairly free of suspended solids; therefore it finds a relatively good market in fermentations. It has been used as the substrate for a number of fermentations such as production of baker's yeast, citric acid, vinegar and alcohol. It has proved satisfactory for growth of *B. megatherium*, a producer of vitamin B_{12}, and could be used for production of dextran or levulan. About 37 million gallons of molasses were used for industrial purposes in 1946; the remaining 36 million were Steffenized.

BEET TOPS. Beet tops are a valuable feed, being rich in carotene, protein and other essential food factors. Most of the nutrients are concentrated in the

leafy parts, not in the stem. Since the stem has a high water content, a number of methods of defoliating the tops are under examination. The leafy material, if it can be readily separated, could probably be dried economically in alfalfa driers. Field curing of tops has also been used, but destruction of carotene and other nutrients is so great that the dried beet tops are useful only as a source of energy. Farm use of these beet wastes is highly desirable, not only to add to the meat supply but also to return mineral elements to the soil. In Europe the value of the molasses and pulp is so great that sugar is considered the byproduct, and some factory operations, such as cossette cutting, is controlled in part by farmer's demands for a pulp that is easy to feed.

STEFFENS WASTE LIQUOR. All the impurities not precipitable by lime in the Steffens house pass into the filtrate. Among them is glutamic acid, or rather a cyclized product, called pyrrolidone carboxylic acid (PCA). Inasmuch as the relative concentration of these impurities can be increased 20-fold or more during the removal of sucrose, recovery of some of them becomes economically feasible. In California and certain other regions the concentration of PCA is sufficiently high to warrant concentrating the waste liquor and processing it for glutamic acid. This is an expensive process, since the PCA must be treated with base (or acid) under conditions that favor production of *l*-glutamic acid and opposes racemization, which means corrosion-resistant equipment. After hydrolysis of PCA is accomplished, the liquor is concentrated and acidified, and glutamic acid is crystallized in acid-resistant crystallizers. Monosodium glutamate is widely accepted as a flavor intensifier (27).

Betaine can also be readily recovered from the waste liquor by acid treatment. Recently evidence has accumulated that it can be used as a poultry feed supplement, replacing part of the choline that is required as a biological methylating agent. Derivatives such as esters, amides and ketones have been made which are stable to acid and, in some cases, fairly stable to alkali and are surface-active, but whether they can compete with similar compounds made from trimethyl amine and chloracetic acid derivatives is questionable.

Other amino acids such as leucine, isoleucine, valine and threonine are present in this waste liquor. They could be concentrated to make a feed supplement. By use of ion exchangers the amino acids might be prepared in U.S.P. quality so that they would be useful in dietary supplements, in post-operative injections or whenever amino acids must be given intravenously.

Johnstown waste liquor or "B molasses" is also a rich source of amino acids. Prior to their isolation, potassium sulfate is crystallized and converted to a potassium fertilizer. Potassium salts can also be obtained from the waste liquors of glutamic acid manufacture.

LIME CAKE. The amount of limestone required for production of lime in the defecation process ranges from four to six percent of the weight of beets sliced. This represents at least one-half million tons of dry lime cake from the defecation process. Generally it is discharged into pits or settling basins, occasionally into streams. The settled lime sludge can be used to increase the alkalinity of soil, but in the western regions this is not a problem. Recycling and reuse in the factory have received attention (16) and appear to be profitable.

Future

We have seen that the sugar-beet industry has developed through the years by application of scientific observations

in the field and in the laboratory. The following groups of professional workers deserve credit: agronomists, for development of hardy, sugar-rich beets; engineers, for designs of new equipment for beet planting, thinning and harvesting; chemists, chemical engineers and sugar technologists, for improvement of factory operations so that recoveries up to 97 percent of the sugar in the beet are now possible, along with extensive use of byproducts. Further developments along all of these lines can be expected, although not much more can be done towards recovery of more sugar except to raise the general factory average.

One point that might be more widely appreciated in the sugar-beet industry is that is should no longer consider itself exclusively a manufacturer and marketer of sugar, but should extend its activities to include other compounds. Thus Steffens waste water can be concentrated, stored and processed for its valuable constituents at off-season periods. Lime cake can be heated to destroy organic matter, and the lime recycled several times prior to introduction of too many impurities (16). Perhaps some use for the polysaccharides in the marc is possible. In any event, the production for sale of chemicals other than sucrose should not represent a revolution in an industry which manufactures its lime and carbon dioxide for its own use and sells beet seed, fertilizer, molasses and feed.

From the growers' point of view the most promising technological advance would be development of a method to treat beets or beet juices so that factory operations would extend over a longer period of time. If this can be accomplished, beets would be harvested at their maximum sugar content with a greater net return to the grower. Work is underway in some laboratories, particularly in Europe, on dehydration of beets and on other methods to achieve this objective.

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Canaigre—*A Desert Source of Tannin*

Canaigre has been in use on a limited scale as a source of tannin for about 100 years. It is easily grown, requires no special attention, and may be the answer to shortages in natural tannin supplies.

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Historical Background

Periodically for the past 70 odd years canaigre[1] (*Rumex hymenosepalus* Torrey) has been the subject of studies by a number of botanists, agricultural workers and chemists interested in the tannin-producing qualities of the roots of this native plant of the southwestern United States.

The plant was first brought to the attention of the United States Department of Agriculture in 1868, at which time a sample of the roots was shipped from Texas. However, through an oversight the sample was mislaid and an analysis was not made until 1878 (21).

Voelcker in 1876 published the first analysis of the roots, and reported that they contained 23.2% tannin (22).

Among the first detailed descriptions of the plant and its culture is an excellent bulletin (2), published in 1892 by the New Mexico Agricultural Experiment Station, which considered this crop along with the more common field crops of wheat, oats, rye, sugar beets and sorghum. The more recent references have appeared as reports 10, 17, 18, 19 and 20 of the work done at the Eastern Regional Research Laboratory, of the Bureau of Agricultural and Industrial Chemistry of the U.S.D.A. and the Division of Drugs and Related Plants.

Enthusiasm for this plant has reached to foreign countries, as witnessed by the lengthy article published by Professor Eitner of the Vienna (Austria) Leather Research Laboratory in 1891 (12). He wrote: " Last year I drew attention to canaigre and pointed out its remarkably good value for upper leathers. Since then I have made careful tests with it upon sole leather and here also I find it of great value. It tans very rapidly and makes the leather full without any brittle substance. My tests are fully confirmed in a larger way in this tannery ".

A few years later, in 1900, the El Paso (Texas) Herald (16) published a feature article which stated that " . . . with the rapid destruction of oak and hemlock . . . the time is not far distant when tanners will have to look elsewhere for a tanning product. Twenty to forty years are required to grow a fair sized tree, whilst in two years as much tannin as

[1] The word " canaigre " is undoubtedly an American mispronunciation of the Spanish " cana agria " (sour cane) by which name the plant is chiefly known in Mexico (14). In some areas of Mexico and New Mexico it is also called " yerba colorado " or " red root ". It is also referred to as " tanner's dock " and " wild rhubarb ".

would be contained in this tree may be produced by canaigre on a few square yards of land ".

Between these early years and the late 1930's when the U.S.D.A. began work on a fairly intensive scale with this plant, little effort was made to study the crop, although several groups attempted commercial production of canaigre tannin in Texas, Arizona, New Mexico and Mexico.

The first recorded attempt to market the roots on a commercial scale was made by Colonel J. C. Tiffany in 1882, while he was government agent for the Apache Indians of the San Carlos Reservation in Arizona (9). The colonel shipped large quantities of the fresh roots to New York, Germany, Austria and England. Unfortunately the shipments fermented and resulted in destruction of the leather they were used on. The demand for the product consequently declined suddenly.

In 1884 a son of the colonel sliced and dried the roots before shipping them, and thus provided an excellent product welcomed by tanners at home and abroad. The project died very shortly, however, because of lack of a steady supply of roots, as at that time no thought had been given to raising canaigre on a large scale as a crop.

In 1886 a tannery was built at Tucson, Arizona, for the use of tannin from canaigre, but disagreement among the stockholders forced closure of the business (9).

In 1887 Mr. R. J. Kerr, of Deming, New Mexico, began large-scale shipments to Scotland, England and Canada. Costly freight rates, however, made the price of the product too high (9) to permit continuation.

By 1892 enough research had been done to produce a non-fermenting semisolid extract with a standard purity of 48% tannic acid. In the same year a factory began production of this material at Deming, New Mexico, which was so well received that more than 2,000,000 pounds were sold on American markets (16).

At the present time the Bureau of Plant Industry, Soils and Agricultural Engineering is conducting studies of the agronomic factors involved in canaigre production, such as site and soil, climatic factors, propagation, selection of planting stock, spacing, fertilizers, and cultural and harvesting practices. The laboratory work designed to study tannin extraction and utilization of co-products is being done by the Bureau of Agricultural and Industrial Chemistry, at its Philadelphia laboratory.

The authors, in cooperation with Mr. Carl Nakayama of Las Cruces, New Mexico, a vegetable producer, made two small field plantings in the spring of 1950.

Botany

Rumex hymenosepalus is a perennial, ranging in height from one to three feet with leaves up to 20 inches long, slightly wavy, with blades rounded or somewhat acute at the base, borne on short thick petioles.

The flowers are bisexual, usually protandrous, medium to large, pinkish-red; panicles six to twelve, without tubercles. Seeds are produced in large numbers and are borne in small clusters on slender pedicels. When ripe they are shiny brown and resemble buckwheat.

A vivid picture of pollination in this plant has been given as follows (6): " Some two to three days before the stamens are ready to shed their contained pollen the rather long, three-parted plumous style curves back at each angle of the achene, the parts projecting between the three inner bracts of the floral envelopes. These bracts only spread as they are crowded apart by the developing stamens ".

" The flower hangs downward, suspended by the rather long-jointed fila-

FIG. 1. A mature wild plant, collected in Arizona.

mentous pedicel. As the pollen ripens the stamens are swayed back and forth by the slightest breeze, and the scattering pollen is carried by the wind to the younger flowers, the stigmas of which are at this time ready to receive it ".

The same authors note an extremely low seed set, and attribute it to the earlier maturing of the gynecium of the individual plant, as compared to the period of maturity of the androecium. They also feel that wind as an agent of pollen transfer is partly to blame.

We have been struck by the fact that canaigre plants seem to exist in widely scattered groups of one to three plants, and that the desert insects of southern New Mexico do not frequent the blossoms at blooming time. Undoubtedly protandry is the major factor involved in the small number of seeds set.

Distribution

R. hymenosepalus is of common occurrence in southwestern United States and northern Mexico. Escobar (13) has found it in the Mexican provinces of Chihuahua and Sonora, and in portions of Coahuila and Baja California. In the United States it is found in southern New Mexico, central and west Texas, Arizona, southwestern Utah, southern Nevada, and in California (15) as far north as the Kern Valley, although more at home south of the Tehachapi Mountains in the sandy lands of the San Bernadino and San Fernando plains, on the San Gorgonia and on the border of the Colorado Desert and in the valleys of San Diego county.

Composition of the Root

Although tannic acid is the most important product for which canaigre is grown, several by-products are available in the form of left-over material after tannin extraction.

The non-tannin constituents analyzed (5) after acid hydrolysis were found to consist, in part, of 25.5 to 36.6% reducing sugars, suggesting a suitably high carbohydrate content for alcohol or organic acid production by fermentation.

The Rogers and Russell (19) analysis of wild roots collected near Las Cruces, New Mexico, in 1937 has a considerably lower figure for reducing sugars. A summary of the table follows. Twenty-five plants were used.

RANGE IN CONTENTS, DRY WT. BASIS

Total Solids	Soluble Solids	Non-Tannins	Tannin	Reducing Sugars	Total Sugars
%	%	%	%	%	%
30.1 to 59.5	28.9 to 55.7	17.7 to 28.7	11.2 to 35.3	2.6 to 15.8	8.1 to 19.6

Quite recently, in 1947, careful attempts were made (10) to produce high purity extracts from canaigre by fermentation, since the sugars in the roots, largely sucrose, interfere with proper tanning procedure.

Although a great number of microorganisms [2] were tried by these workers, none was found which could satisfactorily do the job, mainly because of the adverse effect of the tannin present. A few species, *e.g.*, *Saccharomyces cerevisiae* and a " wild " yeast, gave partial fermentation, but so slow and incomplete as to be considered unsatisfactory.

In 1943 (20) a bacterium was isolated from a shipment of Arizona-produced and prepared canaigre roots which was capable of almost completely decomposing the sugars in the roots without affecting the tannin. The organism is described as a small Gram-negative rod (10), apparently a member of the genus *Aerobacter*. The organism was not used

[2] *Bacillus macerans*, *Bacillus actoaethylicus*, *Aerobacillus polymyxa*, *Lactobacillus delbruckii*, the anaerobes *Clostridium felsineum*, *Cl. acetobutylicum* and *Cl. roseum*, four known strains of *Saccharomyces cervisiae*, two unidentified yeasts, and one species of the mold *Rhizopus*.

FIG. 2. Botanical details of *R. hymenosepalus:* a) entire plant in flower, ×⅜; b) tuberous roots, ×½; c) flower, ×4; d) fruit (utricle), ×3; e) achene, ×5.

successfully to ferment Texas and New Mexico roots. Corden et al. (10) conclude that there is a difference in the chemical composition of the roots of different strains which influences their ability to undergo fermentation by this particular bacterium.

Escobar (13) used extracts of this plant on his ranch in Mexico to treat wounds on stock, and reports that it is chewed by Mexicans to relieve toothache.

Forbes (14) considered the feed value of canaigre after water extraction for tannin, and compared its composition with sugar beet chips analyzed at the Nebraska Experiment Station:

Composition of Dry Matter	Canaigre Bagassee from 1-3-year-old roots %	Sugar Beet Chips %
Fat	0.71	0.68
N-free extract	76.98	62.62
Protein	7.94	9.45
Crude fiber	12.07	22.40
Ash	2.28	4.85

From this analysis it is apparent that canaigre has the advantage in nitrogen-free extract, and has somewhat less fiber. However, the feed is unappetizing, a point that might be overcome by use of molasses and mixing with other feeds to increase palatability.

In a comparison with soft coal and mesquite wood, the latter an important source of heat for the poorer class of people in the Southwest, canaigre was about equal to mesquite and two-thirds as efficient as soft coal in heating potential.

Finally it can be pointed out that the waste material left after tannin extraction may well be treated to hasten decomposition and be used as a source of organic matter to enrich the soil.

Production

Although the Bureau of Plant Industry has been rather active in recent years in studying the factors important to production of this crop, there is little information of recent date available as yet.

One of the basic considerations is that of water supply. Most authors (4, 5, 13, 14) agree that a regular water supply will result in an increased yield. However, a factor to be considered is the point at which water becomes excess and possibly depresses the tannin content. Such a phenomenon is common in guayule (*Parthenium argentatum* Gray), in which the rubber present decreases with increase in water supply.

Inasmuch as the plants make their growth from October to May, late summer or early fall would seem to be the most appropriate time for planting, whether by seed or roots. There appears to be little difference in the yield as effected by early spring or late summer planting of roots (9). Roots set out in late spring will put out leaves in May, die back and then begin growth again in the fall.

Blount (4) reports that seeds set out in October will, by April, grow to roots weighing one to four ounces.

The advantage of root plantings as compared to seed plantings is that in the former there may be a commercial crop after two years, while a seed planting can take from three to four years to reach maturity.

When planting roots, a furrow may be plowed, and the roots dropped into it and covered. Planting distance in the row is best kept at one to two feet, and the rows two to three feet apart. Seed pieces should be set about four inches deep.

There seems to be little choice as regards soil type. Hilgard (15) in California found that the plant grew well on heavy black adobe clays. In Mexico (13) it has been successfully produced on sandy soils, soils high in organic matter, and in soils too rocky for other crops. Undoubtedly preparation of the bed and thorough working of the soil preparatory to planting will make it easier for the plants to get a good start and become established.

Although odd specimens of canaigre have been grown in New York and Washington, D. C., it is best suited to the relatively warm long season climates typified in the Southwest. The plants can withstand extremely low temperatures, for short periods of time at any rate. In the vicinity of Las Cruces, New Mexico, winter temperatures frequently drop to zero, and in 1948 a low of $-6°$ C. was recorded, with no noticeable effects on the canaigre growing wild in the desert.

Harvesting

As noted previously, a crop from root-propagated plants can generally be expected in about two years. Harvesting can be accomplished by means of any machinery used in Irish or sweet potato harvesting, or by the use of hand labor, if necessary. At the U.S.D.A. Field Station in Sacaton, Arizona, the roots have been dug by means of long-handled round-pointed shovels. On other occasions the roots have been harvested by means of a turn-plow which opened the beds, making it possible for hand labor to harvest the roots.

Processing

The roots are washed and then shredded in a machine designed for shredding sweet potatoes. This machine can handle the roots at the rate of one ton per hour. Immediately after shredding the material is hauled on canvas to a drying yard with a cement base. As far as possible, metal is avoided and brooms are used to turn the material as an aid to even drying. The most efficient drying was obtained by spreading the material at the rate of one pound per square foot of yard space, and turning it twice daily. This procedure resulted in well-dried canaigre after 24 hours.

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FIG. 3. Digging wild canaigre near Sacaton, Arizona.

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Fig. 4. A representative basket of wild canaigre roots.

Several efficient methods of extracting tannin have been worked out in the past five years by men in the Bureau of Agricultural and Industrial Chemistry of the United States Department of Agriculture. One of them (1) is a method which utilizes thorough mixing of the crushed material with water, and consequent separation of the liquor from the solids by either filtering or centrifuging. This method is especially adapted to canaigre which is difficult to leach by the usual methods.

In 1947 two methods of extraction were developed, involving water and acetone (17). The water method involved Clarke-Frey, Reed-Churchill and modified outside extractors. The Clarke-Frey extractors gave a high tannin extract, but analytical work was hindered by the presence of starch. The two other types gave less tannin extraction but easier filtering solutions. None of the methods used gave complete extraction.

Fifty percent acetone in a water mixture was used successfully to extract tannin in a Reed-Churchill extractor at 60° C., when the particle size was one to two millimeters. The 50% acetone mixture gave concordant values 3.6 to 6.7 percent higher than obtained by water extraction.

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FIG. 5. Spreading shredded canaigre roots on concrete at Sacaton, Arizona.

The most recent report (18) shows that efficient extraction of tannin by water gives only 80 to 85 percent tannin recovery, as compared to 90 to 93 percent recovery with solvent-water extraction, and that with sufficient solvent, usually acetone, temperatures may be kept comparatively low during the process. The experiments reported in this particular bulletin indicate that the process as set forth is sufficiently promising to warrant additional research to study the equipment needed.

Economic Factors

The question is not yet settled as to whether commercial production of tannin from canaigre is economically feasible. Until recently a large part of the American supply of tannin came from the American chestnut (*Castanea dentata* Mill.). Unfortunately chestnut blight (*Endothia parasitica* Murr. (A. & A.)) has practically eliminated this supply. Various other supplies, such as quebracho (*Schinopsis Lorentzii* (Griseb.) Engl.) from South America, hemlock (*Tsuga canadensis* Carr.) from eastern North America, and *Eucalyptus occidentalis*, have also been dangerously reduced by overuse.

It has been the authors' experience that farmers in irrigated areas will not readily abandon cash crop production. Thus in southern New Mexico it would be difficult, if at all possible, to introduce canaigre as a crop, to replace or even supplement cotton and alfalfa. Land values are too high for a crop that cannot be expected to yield annually. It might be grown, however, on lower priced, non-irrigated land; and if the demand became great enough it might be grown profitably on small acreages of irrigated land.

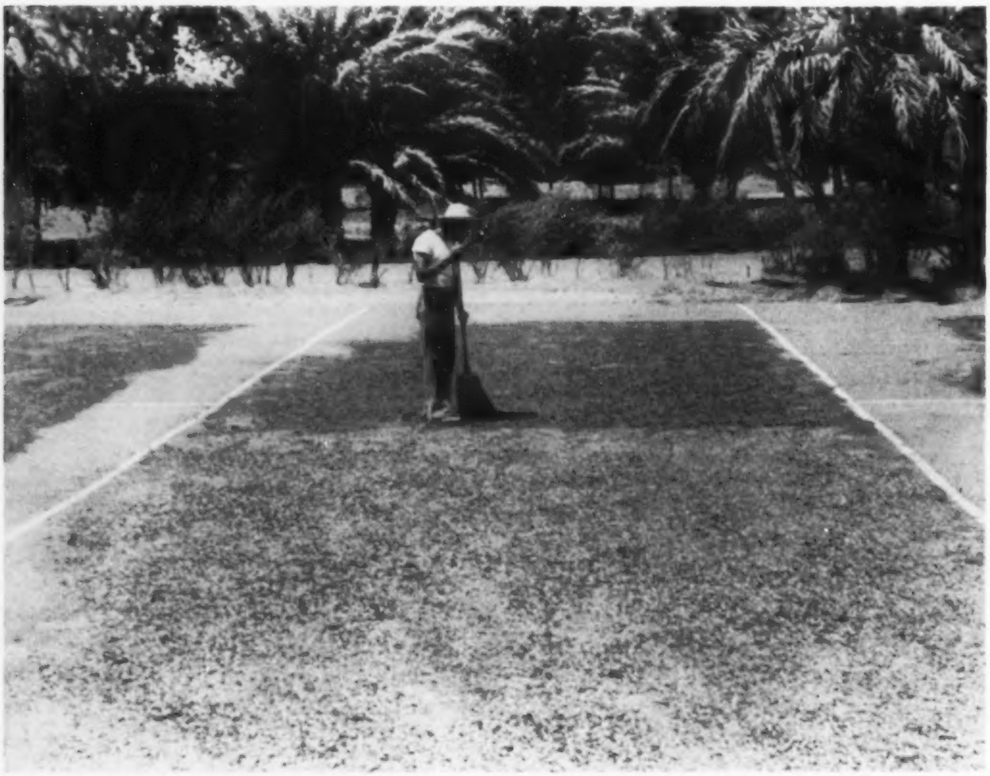

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FIG. 6. Turning shredded canaigre roots with a broom, Sacaton, Arizona.

In the past the difficulty of shipping canaigre to distant markets hindered its commercial development. However, now, with railroad and trucking facilities plentiful, and a diminishing foreign and domestic supply of tannin materials, and the troubled world situation, utilization

of canaigre becomes more feasible, particularly with the research being pursued by the Bureau of Plant Industry, the Bureau of Agricultural Research and Industrial Chemistry, and the Texas Experiment Station.

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The Sweet Potato—*Its Origin and Primitive Storage Practices*[1]

In pre-Columbian times sweet potatoes provided food for the widely separated Mayans of Central America, the Incas of Peru and the Maoris of New Zealand, while two other species of the genus were occasionally used by Indians of western North America.

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Origin

How the sweet potato (*Ipomoea Batatas* Poir.), with its highly palatable and nutritious fleshy roots, has evolved within the convolvulus family is still veiled in mystery; certainly it was long before any written records existed. But the importance and unique characteristics of this food plant justify an effort to put together the fragments of early records and other evidence, and to draw what deductions may be possible regarding its probable origin and dissemination.

In prehistoric times the sweet potato was used for food in two widely separated regions of the world, the tropical Americas and some of the islands of the Pacific. There is no evidence, however, that it was used by the primitive people of Europe, Asia, Africa or Australia. Nor was it known to the ancient civilizations of Egypt, China, Babylon, Persia, India, Greece or Rome. One cannot be sure how long this plant has been used for food. The peoples of tropical Latin America were probably using it many years before the arrival of the Spanish explorers. Columbus found the natives of Cuba using the sweet potato, and later Spanish explorers found it in Mexico and South America (7). No record has been found of the cultivation of the sweet potato by the Indians in pre-Columbian times in the area that is now the United States. Some of the Indian tribes in the western part of this country, however, roasted and ate the roots of a wild plant known as "big root" (*I. leptophylla* Torr.). Since these roots were not especially palatable, they were eaten only when the Indians were hard-pressed by hunger. The Southeastern tribes of Indians did not cultivate the sweet potato until after its introduction by the white settlers. They did, however, use the roots of the wild convolvulus, *I. pandurata* Mey, for food. This root, which sometimes weighs as much as 20 pounds, is popularly known as "man-of-the-earth".

It is possible that the sweet potato was carried into temperate regions of America by the Mayan Indians or by those making contact with them on trading expeditions. Sweet potatoes were grown by Virginia colonists as early as 1648 (21), only 40 years after the establishment of the Jamestown settlement. The early use of the sweet potato by the colonists is an indication either that they

[1] This article, reprinted from *Scientific Monthly*, May, 1951, was read during its preparation by H. W. Krieger, anthropologist, Smithsonian Institution, Irving Rouse, anthropologist, Yale University, and George Carter, geographer, The Johns Hopkins University. Their suggestions have been very helpful, and it is a pleasure to acknowledge them.

had ready access to the West Indies or that they had obtained the vegetable from the Indians.

During the Spanish explorations, probably prior to 1526, the sweet potato was introduced into Spain and thence into other European countries (Oviedo, as quoted by De Candolle (6), p. 55). The plant was known in Europe by the Indian names of " batata " and " padada " (7). The English word " potato " was derived from this source. The sweet potato was introduced into Europe possibly 60 or more years before the Irish potato (*Solanum tuberosum*) and was known there as the " potato ". Confusion arose, however, when what is now called the potato (the Irish, or white, potato) was introduced under the same name. It is known that the white potato was grown in Europe as early as 1588. This knowledge is based on records left by a famous botanist, Caroleus Clusius. Soon after the white potato was carried to England it became known as the " Irish potato ", the sweet potato still being known as the " potato ". Later the sweet potato was designated " Spanish potato " or " sweet potato ".

Scholars endeavoring to trace the origin of this plant have placed considerable emphasis on a study of the wild species in various parts of the world. No single wild species has been found that is definitely known to be the plant from which the sweet potato is derived, however. Botanists classify the present-day sweet potato as belonging to the convolvulus family, to which the morning glories and the giant bindweed also belong. Most of the known wild species of the genus *Ipomoea* differ greatly from present-day cultivated sweet potatoes.

Many of the botanists who have made a study of wild sweet potato species believe that *I. tiliaceae* (Wild.) Choisy is the most closely related wild species from which the cultivated sweet potato may have arisen. This plant grows in tropical America, in the islands of the Caribbean Sea, in the West Indies, and in Florida. It is a twining plant, with stems seven feet or more long, sometimes tuberous roots, and ovate leaves three to four inches long. The flowers, which are three to four inches long, are purple-pink or nearly white, usually with a dark eye.[2] This wild species is not known to be native in any regions other than tropical America and adjacent islands.

Convolvulaceous plants belonging to the genus *Ipomoea* are widely distributed over the world, particularly in tropical areas. Unlike the sweet potato, however, most of these plants do not have a fleshy storage root, and the roots of those species that do are often most unpalatable, or even violently purgative. One cannot help marveling at the fact that such a splendid food as our sweet potato seems to have evolved from such unpromising sources as the wild convolvulaceous plants.

Recent studies of King and Bamford (16) show that most species and varieties of *Ipomoea* investigated are diploids, with the basic chromosome number 15. The two known exceptions are *I. ramoni*, a tetraploid with 60 chromosomes (4 sets) in vegetative cells, and *I. batatas*, a hexaploid with six sets, or 90 chromosomes. Theoretically a tetraploid form might have arisen from a diploid through mutational chromosome doubling; and crossing of a diploid and a tetraploid might have given rise to a

[2] The most conspicuous differences in *I. tiliacea* and *I. batatas* may be seen by the following comparisons: *I. tiliacea:* sepals 8–10 mm. long; stems usually pilose or pubescent and twining; leaves simple or angularly lobed; roots sometimes tuberous. *I. batatas:* sepals 10–14 mm. long; stems usually glabrous and prostrate; leaves simple or variously divided; roots tuberous. These characteristics do not always hold, for many forms or strains of sweet potatoes have pubescent stems, and some are upright, not prostrate, in habit of growth.

triploid which through chromosome doubling would produce a hexaploid type. Interspecific hybrids of *Ipomoea* must be difficult to make, however—at least under some conditions—for in the course of King and Bamford's work, which extended over three growing seasons, more than 500 interspecific and intervarietal pollinations in this genus were made, but none was successful. The complex cytological make-up of the sweet potato suggests considerable complexity of origin. Further cytogenetic studies need to be made of the present-day wild plants showing some similarity to the cultivated sweet potato. Such a study may reveal some important relationships that will throw light on the origin of this important food plant. The usual conclusion to be drawn from the available information is that the sweet potato originated from wild plants growing in tropical America and that this stock was carried to other parts of the world, where it was subsequently grown.

Undoubtedly the present-day sweet potato has undergone many and radical changes during the years in which it has been cultivated and used for human food. Variations in plants may arise both from genetic variation in seedlings and from sports, and mutations are of frequent occurrence in the present-day sweet potato. Sufficient variation may take place even in the vegetatively propagated sweet potato to develop distinct new varieties. To cite an example, some years ago, Thomas White, of the Maryland Agricultural Experiment Station, had brought to his attention, in a field of Big Stem Jerseys, one sweet potato having flesh of a deep, rich, golden color in contrast to the creamy yellow of the rest of the crop. This specimen was saved and used for propagation purposes, and from this start the commercial variety Maryland Golden has arisen.

The people of a temperate climate usually think of the sweet potato as not blooming or setting seed, but in some tropical regions—for example, in Puerto Rico, where this plant has been grown for centuries—it often blooms and sets seed. And some varieties or selections will bloom and set seed in temperate regions. Where natural reproduction takes place by seed, widely different types of plants may arise as the result of genetic variation which is due to natural hybridization of unlike parents. All known forms of sweet potatoes are extremely heterozygous, their seedlings representing a remarkable diversity from their parents. From chance seedlings, which may be quite different genetically, some outstandingly good plants may have been noted and saved for propagation. It is easy, therefore, to postulate that radical changes may have taken place in the sweet potato during sexual as well as during asexual reproduction.

In the early literature dealing with the sweet potato it is sometimes difficult to determine whether the reference is to the true yam (*Dioscorea alata* or other species) or to the sweet potato. The yam differs markedly from the sweet potato. It has slender twining stems, often measuring as much as 20 feet in length. This plant has underground tubers that vary from the size range of white potatoes to enormous yams weighing 30 or 40 pounds and measuring as much as three feet in length. In this country " moist-fleshed " sweet potatoes are often erroneously called " yams ".

A glance at the history of two of the early civilizations in America will throw some light on the origin and antiquity of the sweet potato. In the dim ages of the past there flourished two highly developed civilizations in tropical America: one in Middle America, the Mayan; the other in South America, the Peruvian. The Mayans are a very ancient people. Morley (18) states that pre-Mayan history extends as far back as 3000 B.C. In

some of the later epochs the Mayans evolved a highly developed system of agriculture. They had a number of distinct varieties of maize, which was their main crop, and they also cultivated the sweet potato. The Peruvian civilization, which arose in the Andean highlands, also developed in very ancient times an advanced type of agriculture. Here also maize played an important role and the sweet potato was cultivated (20).

Recent archaeological studies in South America provide evidence that man's occupation of that region goes back into prehistoric times. Junius Bird (5), in his report on excavations in the Huaca Prieta in Peru, concludes that this region gives the earliest record of a farming and fishing community in the Americas. As a guess he places a date on the occupation of this region at possibly as early as 3000 B.C.

The length of the period during which man has lived in the Americas is much greater than was at one time supposed. Recent archaeological excavations in Mexico by De Terra (22) have uncovered a skull and other part of a human skeleton (Tepexpan man) in a stratum to which a date of 9000 or 11,000 B.C. is assigned. Carter (8) reports archaeological studies in a valley in California indicating man's presence in that region as long as 100,000 years ago.

In pre-Columbian times while the sweet potato was fulfilling an important function in the economy of the people of tropical America it was also an important food plant for the Maori of New Zealand. Some anthropologists (4, 13) are convinced that the sweet potato was grown in New Zealand long before the beginning of the Spanish explorations.

Extensive anthropological studies on the Maoris, the early inhabitants of New Zealand, disclose some interesting and valuable facts concerning the importance of the sweet-potato plant and the intimate way in which it was interwoven with the life of the people. Since they grew no grain the sweet potato became the main food crop. They called it " kumara ". The origin of kumara, insofar as this primitive people is concerned, is closely connected with their mythology. The importance of this plant as food probably accounts for their giving religious significance to its origin and also for the elaborate ceremonies connected with planting, cultivating, digging and storing it. Such ceremonies are often associated with the principal food crops of primitive agricultural peoples the world over. The North American Indians carried out elaborate ceremonies with corn, and in the mythology of many peoples certain gods and goddesses are looked upon as the tutelary or protecting spirits for cultivated products. The ceremonies of the Maoris began at planting time, when whole roots were planted directly in the field. Much of the work was done in unison with a song or chant of the priestly adept or chief. At important operations in the growing, digging and storing of the crop certain other ceremonies were performed; and at the conclusion of the digging and storing there was a great feast. In one of the smaller feasts, Colenso (12) says they used 2,000 bushel baskets of sweet potatoes.

There is evidence that the sweet potato was introduced into New Zealand from some of the Polynesian Islands at a very early date. One writer (2) states that it was brought there four or five generations before A.D. 1350. There is a tradition that the Maoris, not finding the kumara on their arrival in the country, sent an expedition back to their old home in the Pacific Islands to secure a supply for seed purposes. This expedition probably brought back a wide range of varieties. Colenso states that no fewer than 30 varieties have come to his attention, all with separate names and very

divergent characters. The sweet potato sometimes blooms in New Zealand but is not known to set seed there; hence, new varieties probably arose as sports. Even though the Maoris used crude wooden tools, they developed relatively advanced methods of culture. They planted whole roots directly in the field—*i.e.*, no plant bed was used—and they planted in raised hills. Where the land was not right according to their ideas, they carried baskets of sand or gravel to make it more suitable. This material was often piled around the plants to a depth of three or four inches, at an enormous expenditure of effort. In one region alone more than 200 acres were artificially covered with gravel.

It appears probable that the sweet potato was being cultivated and used for food in two widely separated regions of the world before communication was known to exist between these regions. The idea first prevailed that the Spanish explorations and conquests were responsible for the introduction of the sweet potato into Oceania, where it was subsequently highly prized and disseminated. When it became known, however, that the sweet potato had been used in New Zealand many years before the Spanish expeditions in America, it was necessary to postulate some other method of transporting it from South America to Oceania. It is generally conceded that man has been the chief agent in the dissemination of cultivated plants, and Carter (9) emphasizes the importance of man in the carrying of cultivated plants across large bodies of water. He also emphasizes the fact that plants became markers of the ramblings of man.

Hornell (15) has made a special study of the various possible ways in which the sweet potato could have been taken from the west coast of South America to Oceania. This study included the type of rafts used by the Polynesians and an analysis of the ocean currents that would aid in getting a craft from Polynesia to the west coast of South America and thence back to Polynesia. From the tenth to the fourteenth centuries the daring and adventurous Polynesians made long and hazardous trips over the Pacific Ocean. Voyages were made between Hawaii and Tahiti, probably via the Marquesas and the Fanning Islands. These voyages must have involved distances of more than 2,400 miles, with probably only the seasonal flight of migratory birds as a guide (10). The distance from Easter Islands, the last land on the route from New Zealand to the west coast of South America, is 2,200 nautical miles. Hornell believes that the trip from Polynesia to South America could have been made by taking a southern course and finally following the Peruvian Current up the coast of South America. The distance one way would not be greater than 2,500 miles, and it is known that trips as long as that were made by the Polynesians. More difficult still would be the return voyage, since that would involve reaching a particular tiny island. The return could have been accomplished by going northwest from Peru, getting into the equatorial current, and making a landfall on the Marquesas Islands. From these, the travelers could easily sail from one island to another. It was a common practice among the Polynesians to carry food, plants, animals, and in some cases women, on their long dangerous voyages so that if they were cast ashore on an uninhabited island they would be able to maintain themselves there.

Whether the sweet potato was developed in the tropical regions of America and transported to the Polynesian country in very early times, or whether it was developed in Polynesia and carried by the Polynesians to America, is still a subject for speculation. It is usually assumed that the sweet potato is of American origin.

When the Spanish explorations took place the sweet potato that was then

known in tropical America was introduced into the Philippines, as well as into other Spanish possessions.

The sweet potato was not taken to China until within historical times. The investigations of Laufer (17) give us the interesting and graphic story of how the sweet potato reached China and Japan. In 1593 the province of Fukien in southern China, presumably because of the ravages of a typhoon, was stricken by famine. The governor of the province, Kin-Hio-tseng, sent a commission to Luzon in the Philippines in search of food plants that might relieve the pitiful plight of his people. After many adventures in Luzon the commission secured some seed stock roots of the sweet potato, and in 1594 it returned home with this novel plant. The new plant was greeted with unbounded joy. Although the economic value and the high nutritive properties of the newcomer were at once recognized, it was not until 1786 that an imperial order was issued to encourage the cultivation of the sweet potato as a means of preventing famine.

There are several different accounts of the movement of the sweet potato from China to Japan. Laufer reports that about 15 years after its introduction into Fukien the sweet potato was transported to Formosa, and to the Luchu Islands as early as 1605. At that time the Luchuans still formed a kingdom of their own, although recognizing the sovereignty of the Chinese emperor. Nugun, the superintendent of the Chinese settlement in Napa, the chief town of the archipelago, presented a native village chief, Masatsune, with cuttings of the plant. He eagerly studied its cultivation and promoted it in his country. A memorial pillar has been erected in front of Nugun's tomb, and he is canonized under the name "Mmuushume", that is "Ancestor of the Tuber". A Japanese farmer, Maeda Riuemon, a native of the province of Satsuma, made the acquaintance of the sweet potato while paying a visit to Luchu in the latter part of the seventeenth century. On his return home he introduced its cultivation into Satsuma, and from there it spread over the northern provinces of Japan. Riuemon's tomb is known as "Kara-imo-den" ("Temple of the Sweet Potato"), and there every spring and autumn the soul of this simple farmer receives offerings from his grateful countrymen.

The word used for the sweet potato in different parts of the world has been the object of much interest and study by certain ethnologists. Christian (11), who has made a special study of the words used in Polynesia and other parts of the world and compared them with some basic Sanskrit words, says:

"The various Polynesian forms, 'humara', 'kumala', 'umara', 'umala', 'uara', 'uala' and 'uwala', for the sweet potato, form a curious chain of evidence. In the Northern Philippines they call it 'kamote'. . . . Cf. Malay 'barat' and Sanscrit Barata (S. India). . . . With 'Kumala' compare Sanscrit 'kauwal', the lotus, 'Kumthla', and 'kumad' and 'kumud', the white esculent lotus (*Nymphoea esculenta*), also Sanscrit 'kamal', a lotus. The Quichuan (Peruvian) word for sweet potato is 'kumara'. The similarity of the Peruvian and Polynesian words for sweet potato may be important in tracing the origin of this plant. The question arises as to whether the kumara was brought from India to South America by pre-Columbian navigators".

History of Curing and Storing

No storage problem existed when the sweet potato was growing in its native tropical habitat—the potatoes were dug as needed. However, after this plant was taken to a country having a temperate climate, such as New Zealand, it was necessary to keep the edible part, the fleshy root, alive and sound throughout the winter in order to have it avail-

able as winter food and to grow more plants the next season. The sweet potato differs from grain in that the edible portion is not a dried seed that is easily stored and transported but a fleshy root that is highly perishable when storage conditions are not favorable. The storage treatment of the sweet potato is quite different from that of most food products, and successful storing from one growing season until the next demands certain rather exacting procedures.

Some aspects of this problem that are now common knowledge must have been learned with great difficulty and only after many failures. The two fundamental principles of keeping sweet potato roots from rotting and in a viable condition until planting time are proper curing and relatively warm storage. Even today, however, in spite of our many ways of disseminating knowledge, the importance of these two principles is not adequately appreciated by some people engaged in the handling and marketing of the sweet potato. What meager and fragmentary history we have of the curing and storing of this crop must be gleaned from a number of obscure sources or deduced from such sources as ethnological accounts of the peoples of temperate climates who first used the sweet potato for food.

A brief discussion of the physiology of the stored sweet potato is necessary before reporting the early records on storing. While the sweet potato is growing in the field there is an inflow to the roots of food materials manufactured by the leaves, which is suddenly stopped when they are dug. The roots then undergo a period of "curing". Usually special conditions of temperature and humidity are supplied during this curing period, although in some favored areas storage house temperatures and humidity conditions are such that little artificial control of these factors is required. One of the important and obviously practical functions of curing is the formation of periderm, or callus, over the wounds, particularly those where the roots have been severed. This periderm, or wound callus, helps to prevent the entrance of rot organisms.

After curing is effected a different treatment is necessary for storage, but there is apparently no sharp dividing line between a cured and a non-cured sweet potato. In the curing treatment we seek to provide the optimum conditions for certain physiological and structural transformations to take place. In storage, on the other hand, we endeavor to provide conditions that will enable life activity to proceed, but at as slow a rate as possible. The conditions now used for curing and storing the sweet potato are different from those required by many other plant products, such as apples, turnips, cabbages and white potatoes, for example. The present-day curing practice ordinarily consists of subjecting the freshly dug roots to a high temperature (85–90° F.) and a high relative humidity (85–90 percent of saturation) for a week to ten days. Since curing is vital to the storage life of sweet potatoes, it would be interesting to know how and when this important practice originated. A study of the food-handling practices of certain primitive people and of the early literature on the sweet potato indicates that some kind of treatment, which at least partially fulfills the physiological need of curing, has been known and practiced for many years.

The sweet-potato storage practices of the Maoris of New Zealand—early inhabitants of a temperate climate—have been in effect for many centuries (4). These people followed a fixed ritual when they harvested and stored sweet potatoes. On the appointed day, when all the signs were right, digging was started in the morning, but not before sunrise. By noon the digging ceased, and in the afternoon the sweet potatoes were stored. The Maoris used well-constructed underground storage houses dug in the side of

a hill. The sweet-potato house was probably the most important building in the village, and the entrance was often elaborately carved with figures to keep out evil spirits and thus prevent spoilage. The usual storage procedure was to cover the floor with a layer of gravel an inch deep and then with a layer of rotten wood. The seed stock for the next year was selected and stored in the back of the house, separated by fern leaves from the sweet potatoes that were to be used as food. After the seed stock was put into the house, the best of the food potatoes were stored. Finally, the bruised and cut roots were stored near the entrance, where they would be used first. Any important task involving the sweet potato was done communally, so as to finish it the same day it was begun. The storage house was thus quickly filled. It was then tightly closed, and a charm put upon it by the priest adept (3). No one was allowed to enter until a certain period of time had elapsed; then the charm was removed by appropriate ceremonies. During the charm period, when the house was full and tightly closed, conditions were undoubtedly favorable for curing. High relative humidity and a comparatively high temperature would soon develop as a result of the respiratory activity of the potatoes themselves. The Maori introduced the sweet potato into their country from some Polynesian island where the climate was such that there was no storage problem, and, since the sweet potato is very exacting in its storage requirements, it is a noteworthy accomplishment of this primitive people that they developed a successful method of preserving this important food plant for seed and food from one season to the next. The Maoris, however, must have experienced losses from rot, since the priests told the people that unless all points of the ritual were strictly followed the sweet potatoes would spoil (4).

Let us now return to the subject of the early literature in the United States on the storing of sweet potatoes. The meager and scattered writings of early colonial times dealing with this subject indicate that it was known that warm storage is necessary for the successful keeping of sweet potatoes. Beverley, in his history of Virginia written in 1705, makes the following statement about the sweet potato (7):

"Their potatoes are either red or white, about as long as a Boy's leg, and sometimes as long and big as both the Leg and Thigh of a young Child, and very much resembling it in Shape. I take these kinds to be the same with those, which are represented in the Herbals, to be Spanish Potatoes. I am sure, those called English or Irish potatoes are nothing like these, either in Shape, color or taste. The way of propagating potatoes there, is by cutting the small ones to pieces, and planting the cuttings in hills of loose earth: But they are so tender, that it is very difficult to preserve them in the Winter; for the least frost coming at them, rots and destroys them; and therefore people bury 'em under Ground, near the Fire Hearth, all the Winter, until the Time comes that their seedlings are to be set".

The importance of curing sweet potatoes was apparently realized long ago by Europeans. As early as 1525–35 Oviedo, as quoted by Gray and Trumbell (14) wrote: "When the Batatas are well cured they have often been carried to Spain when the ships happen to make quick passage but more often they are lost on the voyage". He places special emphasis on the importance of curing to prevent rot. It is true that curing in those times did not carry the definite connotation that it now carries. Even today, however, we know very little about the physiology of curing sweet potatoes.

It would be interesting to know how a fact of such fundamental importance as warm storage in the keeping of a food

product was learned. It may have been that information was acquired many generations ago when an Indian tribe on the border of a tropical region carried the sweet potato from a tropical to a more or less temperate climate. Probably after many failures in keeping sweet potatoes they finally discovered the proper method. After the essential features of successful storage were discovered, the method could be readily transmitted from person to person wherever the sweet potato was carried. For the colonial Virginia farmer the idea of providing warmth to preserve such a food product must have been quite an innovation. His experience with other products had taught him that apples, cabbage, turnips and potatoes keep better in cool than in warm storage, and he would naturally expect to store sweet potatoes in the same way.

Among the records of sweet-potato storage are the details of the construction of a sweet-potato cellar in which heat was used (19). The author recommended that the sweet potatoes be piled on poles and a smoky fire be made every day for three or four weeks. He put special emphasis on smoke, but heat rather than smoke was probably the important factor. This is one of the earliest records of the use of heat in the curing of sweet potatoes.

Knowledge of the difficulties in the storage of the sweet potato is reflected in the writings of Sir Joseph Banks (1) on some horticultural observations selected from French authors. He says: ". . . the slightest scratch predisposes them to rot. They must be kept free from frost and damp; if exposed to either of these, they exhale an odour like that of the rose, and rot immediately . . . ".

At any rate, the transfer from a tropical to a temperate climate necessitated the devising of methods of storage to provide food in winter and to keep the roots in viable condition until the next planting season. Somehow the early users of the sweet potato learned the fundamental requirements for successful winter storage, the need for a cure or conditioning treatment, and for a warm storage place.

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Hybrid Vigor in Cotton—*Cytogenetic Aspects and Practical Applications*[1]

The utilization of heterosis in first generation hybrids constitutes one of the more important contributions of plant breeding to agricultural production. Heterosis is pronounced in interspecific hybrids of Gossypium and is manifest in certain intraspecific crosses. The utilization of hybrid vigor in the commercial production of cotton is a current problem of much interest.

HAROLD D. LODEN AND T. R. RICHMOND[2]

Introduction

Hybrid vigor, or heterosis, has long been utilized in obtaining increased production of asexually propagated plants, but its use in such species has been more a function of the method of propagation than a systematic improvement in combining ability. Utilization of heterosis in commercial corn production has been one of the most far-reaching achievements of plant breeding and applied genetics. In the words of Moore (48), " Hybrid corn yields for the country as a whole average 25 percent above those of open-pollinated corn. In the 4 years 1942–45, United States farmers grew an extra 2 billion bushels of corn because of hybrids. In 1945 alone this increase was 600 million bushels, worth three-quarters of a billion dollars ". Kiesselbach (37) reported that 78 percent of this country's corn acreage was planted to hybrids in 1949, with the percentage in eight states being 94 percent or more. Ashton (4) stated that only 0.1 percent of total corn acreage was planted to hybrids in 1933.

The employment of heterosis in commercial production of hybrid corn affords the best known example of a most important axiom—the practical utilization of vigor in first generation hybrids is dependent upon the production of large quantities of seed at a minimum of expense. The corn plant is admirably adapted to hybrid seed production because its imperfect flowers facilitate emasculation (detasseling) and a relatively large number of seeds are produced on each rachis (cob). The problem of hybrid seed production in large quantities is greatly complicated in crops which have perfect flowers and are either partially or predominantly self-fertilized; such is the case in cotton.

There is, at present, great interest in the possible utilization of heterosis in cotton production. However, the phenomenon of hybrid vigor doubtless has been observed in cotton from the time of

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the first controlled hybrid. Mell (47), in 1894, published the first known account of increases in certain measurements of agronomic and fiber properties in cotton hybrids as compared to the parents which entered the cross. Circular Number 96, USDA, Bur. Plant Industry (1911), states, " It has long been known that hybrids between Upland and Egyptian cotton produce lint of superior quality. The hybrids are also more vigorous and productive than pure-line varieties and better able to withstand unfavorable conditions. Many attempts have been made to breed superior hybrid varieties, but the later generations always prove inferior to the first, or to the parent varieties. Many of the plants have short or sparse lint and are weak and infertile ". This same publication also states, " Accepting the fact that the superiority of the hybrids is limited to the first generation, other possibilities of utilization are being investigated. Experiments have been made with two methods of producing hybrid seed, hand pollination and natural crossing by bees. The former process would be rather expensive, but the methods have been so simplified that the cost would not be prohibitive. The production of hybrid seed through natural crossing by insects is facilitated by planting the parent varieties in alternate rows. As only a part of the seed will produce hybrid plants, the feasibility of this method depends on the possibility of recognizing the hybrids in the early stages of development and pulling out the remainder of the plants. Studies of the characters of young seedlings have shown that the hybrids can be distinguished in the early stages of growth. The proportion of hybrids in any particular lot of seed would depend, of course, on the number and activity of bees or other cross-fertilizing insects at the time of flowering, and this varies greatly in different localities and in different parts of the season. The utility of the hybrids would be increased if two or more crops of cotton could be obtained from the same plants. . . . The readiness of the cotton in forming subterranean buds on the overwintered roots suggests the idea that cuttings would callous and root readily under the same conditions and thus open up a third possibility of utilizing hybrids by propagation from cuttings. The first attempt of this kind was made in May, 1911, with cuttings of new-wood branches that had developed on overwintered plants. Notwithstanding the lateness of the season and the absence of any special care or precaution to induce the rootings of the cuttings, about 10 percent survived and grew into vigorous and productive plants ".

It is evident that, at an early date, cotton breeders were cognizant of the probable value of F_1 hybrids in commercial cotton production and were investigating possible methods of utilization. Present-day techniques and scientific advancements have added only one other possibility beyond those suggested above, that being the possibility of utilizing self-sterile, semi-sterile or male sterile types in the production of F_1 seed. Most of the early experiments on hybrid seed cotton production involved crosses of Upland (*Gossypium hirsutum* L.) and Sea Island (*G. barbadense* L.). The value of such hybrids for the limited production of certain " specialty " fibers cannot be completely discounted; such production, however, would be definitely limited to F_1 seed. The use of F_2 or advanced generation seed would be impractical because of extreme (transgressive) segregation and sterility, the latter having been shown by Stephens (64) to be due, at least in part, to cryptic cytological differences which appear to exist between even the most closely related species of *Gossypium*.

The practical application of heterosis in extensive cotton production in the Cotton Belt of the United States appears to lie in the use of intraspecific hybrids of *G. hirsutum*.

The purpose of this paper is to present reported evidence of heterosis in cotton, and to give a critical discussion of the possibilities of utilizing the different methods of hybrid seed cotton production.

Interspecific Hybrids

As early as **1894** Mell **(47)** reported hybrid vigor in F_1 plants resulting from interspecific crosses of *Gossypium*. Balls **(7)**, working with crosses of *G. hirsutum* and *G. barbadense*, states, " The most striking feature is the intensification of certain characters which results when two botanically dissimilar cottons are crossed together. This intensification is shown in the height of plant, the time of flowering, the length of lint, the size of seed, probably in the fuzziness of the seed, etc." Balls **(8)** later reported an increased number of nodes and greater internodal length in F_1 plants between the same species.

Cook **(15)**, in crosses of Egyptian (*G. barbadense*) and Kekchi (*G. hirsutum*), found the F_1 plants to be higher in quality of lint than either parent, and he also noted increases in the F_1 in the expression of such characters as bractlet size, general vegetative growth, number of bolls, and locks per boll. With regard to the latter he reported, " There were about three times as many 5-locked bolls as 4-locked, whereas the parent varieties showed at Yuma only about equal numbers of 5-locked and 4-locked bolls ". In discussing the fiber characters of the F_1 plants Cook stated, " Instead of becoming shorter than in either of the parent stocks, the lint of the hybrids between Upland types of cotton and the Egyptian types is longer than either parent. The strength of the fiber is notably improved as well as length ". In this same paper Cook was probably the first to propose that the heterosis found in F_1 plants from crosses of *G. hirsutum* × *G. barbadense* be used commercially. In this connection he stated, " It has become apparent in experiments that large proportions of hybrid seed can be obtained by planting two types of cotton close together and allowing the bees to cross-fertilize the flowers. It also appears practicable to raise fields of hybrid plants by sowing seed of Kekchi plants cross-fertilized with Egyptian pollen. The Kekchi seedlings can be easily recognized and removed, leaving only the hybrids to mature ".

Kearney **(35)**, working with crosses between the varieties Holdon (*G. hirsutum*) and Pima (*G. barbadense*), stated, " In a field of either type of cotton, first generation Upland-Egyptian hybrids are always conspicuous because of the vigor and fertility of the plants. The conjugate generation (F_1) of Holdon × Pima exhibited heterosis or intensification of most of the size characters ". In this work it was found that the F_1 exceeded the greater parent in plant axis length, internodal length, leaf length, leaf width, bract length, corolla length and length of pistil.

Ware **(75)**, in crosses between Pima (*G. barbadense*) and Upright (*G. hirsutum*), studied height of plant and node number. He noted no increase in node number in the F_1; however, there was a very marked increase in plant height. From these experiments he concluded that " hybrid intensity was due to an increase in the length of internodes and not to addition of joints or nodes plus internodes ". Ware **(76)** later worked with three different interspecific crosses: (*a*) Pima × Winesap, (*b*) Pima × Upright and (*c*) Sea-Island × Winesap, and noted an increase in seed weight and lint index in the F_1 plants over the parents.

From experiments involving three different crosses of *G. hirsutum* × *G. barbadense* Ware (77) reached the following conclusions: " First generation hybrid vigor was expressed in a decisive manner by some of the characters in the three crosses. . . . Heterosis is outstanding in general plant growth, in height of plant, in vegetative and fruiting branch length, in size of leaves, in amount of foliage, in abundance of fruiting, in length of bolls, and in weight of seeds. Hybrid vigor occurs in the F_1 generation of species crosses in cotton, but is not expressed by all plant characters ".

Vysotskii (73), working in Russia and using crosses between American and Egyptian cottons, found without exception increased boll production and diminution in shedding in the F_1 plants and also noted a considerable increase in oil percentage, higher percentages of cellulose and a lower salt content in fibers.

In a cross between Half and Half × Sea Island, Ayers (5) found an expression of hybrid vigor in height of plant, number of fruiting branches and production. In the same paper the following observations were reported on an F_1 cross between Half and Half and Pima: " Significant increases over the more vigorous parent, Pima, are shown in height of plant, number of fruiting branches, and number of nodes. The interspecific crosses exhibited general heterosis in most size characters ".

According to Jenkins, Hall and Ware (32), " When Upland cotton is crossed with either Sea Island or Egyptian cotton, hybrid vigor or heterosis in the F_1 is expressed in many of the plant characteristics ". In an experiment designed to measure the heterosis in plant size exhibited in F_1, these investigators studied 27 Upland × Sea Island crosses, four Upland × Pima, five Upland × Hopi and nine Hastings Upright × Normal crosses. Based on this investigation the following conclusion was given: " Hybrid vigor in plant size as expressed within Upland species appears to be negligible, very pronounced between North and South American types, and rather evident between Upland and Hopi ".

A summary of heterosis reported during the past 50 years for various characters in F_1 hybrids of *G. hirsutum* × *G. barbadense* is given in Table I.

Hutchinson, Gadkari and Ansari (29) expressed the view that hybrid vigor in cotton finds important expression only in interspecific crosses, there being a relative absence of hybrid vigor in intravarietal crosses compared to other plants.

Heterosis also has been noted in crosses involving the 13- and 26-chromosome cottons, even though such F_1 hybrids usually are sterile. Deasi (17) obtained a hybrid between *G. herbaceum* and *G. hirsutum*, which proved to be sterile but was very vigorous in growth, producing 532 flowers in a single season.

Intraspecific Hybrids

Intervarietal Crosses. Lately the expression of heterosis in intraspecific crosses of *Gossypium* has been studied with the specific objective of determining the extent of heterosis which may be exhibited in such crosses. Kime and Tilley (39), in discussing the general opinion of cotton breeders relative to heterosis in intraspecific crosses, state, " It has been generally assumed that hybrid vigor does not occur in crosses within cotton species ". According to Brown (11), " First-generation hybrids are frequently larger, more vigorous and more productive than their parents. Many of them are very interesting and very promising, but no great amount of importance can be attached to them, because they are not likely to reproduce their valued qualities ". This statement is significant in that it points

out two pertinent facts: first, that heterosis is found only in certain intraspecific crosses of *Gossypium*; and, second, that the efforts of cotton breeders have been directed in use of subsequent generations resulting from promising F_1's and not in possible means of utilizing the F_1 hybrids as such.

A review of the literature reveals an occasional reference to the expression of heterosis in F_1 generations of intraspecific crosses of *Gossypium*. It is believed, and current investigations substantiate the feeling, that the list of intraspecific crosses in which an appreciable amount of heterosis has been exhibited would have been quite extensive if all of the cases observed had been recorded and published.

Due to the lack of experiments conducted to determine the amount of heterosis in intraspecific crosses of *Gossypium*, much of such information reported has been incidental to other investigations. In certain instances it was reported because it was observed in investigations in which an expression of heterosis was not anticipated. A good example of this is that reported by Hutchinson, Panse and Govande (30). These investigators were working with three intraspecific crosses of *Gossypium arboreum* L. in a study of the inheritance of staple length and ginning percentage; the strains used as parental lines had been self-fertilized for seven generations. Germination, number of the nodes at which the first fruiting branch appeared, yield, staple length and ginning percentage were recorded for P_1, F_1, and F_2 generations. Heterosis in the F_1 resulted in a significant increase over the mean of the parents in staple length, ginning percentage and yield, even though the parents did not differ significantly in all cases. Germi-

TABLE I

SUMMARY OF CHARACTERS IN WHICH HETEROSIS HAS BEEN REPORTED IN F_1 HYBRIDS OF *Gossypium hirsutum* × *Gossypium barbadense*

Character	Investigators
General vegetative vigor	Cook (15), Ware (76)
Height of plant	Ayers (5), Balls (8), (9), Kearney (35), Ware (75), (76)
Number of nodes	Ayers (5), Balls (9), Kearney (35)
Length of internode	Kearney (35), Ware (75)
Length of vegetative branch	Ware (75)
Length of fruiting branch	Ayers (5), Ware (75)
Number of fruiting branches	Ayers (5)
Size of leaves	Ware (75)
Leaf width	Kearney (35)
Leaf length	Kearney (35)
Leaf index	Kearney (35)
Bractlet size	Cook (15), Kearney (35)
Corolla length	Kearney (35)
Pistil length	Kearney (35)
Size of stigma	Kearney (35)
Yield of seed cotton	Ayers (5), Balasubrahmanyan and Narayanan (6), Cook (15), Kearney (35)
Number of bolls	Cook (15), Vysotskii (73), Ware (75)
Boll size	Cook (15), Ware (75)
Number of locks per boll	Cook (15)
Size of seed	Balls (8), Ware (75)
Length of lint	Balasubrahmanyan and Narayanan (6), Balls (8), Cook (15)
Time of flowering	Balls (8)

nation of the F_1 exceeded the mean of the parents in each instance but was significant in only one. In discussing these results, it was stated, "Plant-breeding work in cotton is based on self-fertilization and the isolation of homozygous lines. No difficulty has arisen from loss of vigor on selfing, and heterosis has only been recorded in interspecific crosses. It was not expected, therefore, that evidence of heterosis would be obtained in the present experiment, which involves intervarietal hybrids only. Heterosis proved to be large and important, however, in all characters studied except germination. Even in the cross between the two higher yielding strains, the F_1 outyielded the higher yielding parent by about 20 percent".

Instances have been reported in which no heterosis is exhibited in F_1's of intraspecific crosses. Cook (15) reported a weakened condition in the F_1 of a cross between Upland and Kekchi. Kearney and Wells (36), working with two varieties of *G. barbadense*, Pima and Gila, found no expression of heterosis in boll index, leaf index, or fiber length, the means of the F_1 being, in general, intermediate between those of the parents. Ware (75) found no pronounced increase in vigor of the F_1 or F_2 resulting from crosses among Upland varieties. Jenkins and Harrell (33), in reporting a genetic study involving two contrasting varieties of *G. hirsutum*, Greenseed and Rowden, made no specific mention of hybrid vigor; however, data on a number of characters were given for parents and F_1. No heterosis was indicated for lint length, lint percent, seed weight (gm. per 100), number of bolls per plant and pounds per 100 bolls of seed cotton. All values for the F_1's were approximately intermediate between the two parental means. In the character, seed cotton per plant, a slight increase over the mean of the higher yielding parent was recorded. Murray (49) studied lint length in six strains of *G. hirsutum* crossed in all possible combinations and concluded that heterosis was not an important factor in the expression of lint length.

Koshal, Gulati and Ahmad (40), working with the same strains of *G. arboreum* as used by Hutchinson et al. (30), found heterosis to be significant in fiber length and maturity (especially the former) with no heterosis exhibited in fiber weight per unit length. Ganesan (19), using the same three strains, compared selfed vs. crossed seed in a study of the manifestation of hybrid vigor in the seed. It was found that the seed of the F_1's were 21–41 percent heavier than those of the selfed parents, the greatest increase in weight being mostly in the cotyledons. Ramiah (52), in crosses of different ecotypes of *G. arboreum*, found clear-cut heterosis for all characters studied, the magnitude varying in different hybrids.

Ayers (5), in a number of different intraspecific crosses of *G. hirsutum*, studied the following characters: height of plant, number of fruiting branches, length of fruiting branches, height of first branch, number of nodes and production of seed cotton. The cross of Half and Half × Kasch did not exhibit heterosis for any of the characters. In a hybrid of Half and Half × Lone Star, hybrid vigor accounted for a significant increase in yield over either parent, the mean yields of the parents being 84.417 and 79.930, respectively, and the yield of the F_1, 151.585 grams. A significant difference in height of the first fruiting branch was noted in a cross of Half and Half × Lightning Express, the F_1 having its first fruiting branch 3.067 cm. nearer the ground than the more vigorous parent.

Several extensive investigations of expression of heterosis in intraspecific crosses of *Gossypium* have been conducted recently. In view of the different approach of these investigations to the

same general problem it is deemed advisable to discuss each in some detail.

Kime and Tilley (39) selected lines of Coker 100, Stoneville and Deltapine 11A during the period of 1936–1940. These lines were inbred from two to four generations. The F_1, F_2 and the parental lines for six crosses of the four varieties were planted in a split-plot design for the years 1943, 1944 and 1945. Studies were made on the following characters:

Character	Years studied
yield of seed cotton	3
yield of lint cotton	2
percentage of lint	2
rate of blooming	3
earliness of opening	3
size of bolls	3
lint index	1
seed index	1
height of plants	3
weight of plants	3
fiber strength (Pressley)	1
fiber length (U.H.M.)	1

No evidences of heterosis were observed for percentage of lint, height of plants, fiber strength or length of fiber, the F_1 means being below that of the higher parent. Bloom counts of the F_1 generations were significantly higher than the most vigorous parents in 1943 and 1944, being equal to them in 1945. The F_1 plants differed significantly from the earlier parent in opening of early bolls in 1943 and was equal to or slightly greater in the other two years. Boll size, as determined by the average weight of seed cotton per boll, was barely significant in the F_1 in 1943, with no difference in 1944 and 1945. Lint index of the F_1 was found to be significantly higher in three of the crosses in 1943, the only year this character was studied. Seed index (weight in grams of 100 seed) was studied only in 1943 with no significant differences noted. Weight of plant, as determined by air-dry weights of plants after shedding of leaves, was not significant, the F_1 being approximately equal to the heavier parent in each of the years. However, it was stated that, "Although no measurable differences were found in plant growth, the F_1 hybrids in the 1945 test appeared to be more vigorous than their parents when the plants were 10–15 inches tall. In looking down the rows the F_1 plants appeared to be broader and to have thicker foliage. A disinterested person who was not familiar with the layout of the experiment was able to pick out the F_1 in each split plot in about 70% of the cases".

The most interesting and significant data presented were those relative to yields of seed cotton, with yields of lint cotton following the same trend. Higher yields were recorded for each of the F_1 generations than for the respective most productive parents during all three years. However, significant differences were not recorded for all crosses for all years. The investigators stated, "The three-year average yield for each cross showed the F_1 to be highly significant (1% point) over its best parent in five crosses and significant in the other cross". The above statement does not, however, reflect one of the more important practical considerations relative to the performance of a hybrid, *i.e.*, its performance year by year. To illustrate, the F_1 of Coker 100–1–1–1 × Stoneville 2B–3–10 was highly significant for the three-year average over the most productive parent for the same period; however, it does not significantly exceed the higher parent for any single year. This is also true to a lesser extent in the other crosses; only one hybrid, Stoneville 4B–2–1–1–1 × Deltapine 11A–5, showed a significant increase in yield over the higher parent for each year. The three-year average figures would not appear to be a practical criterion to use in judging the performance of hybrids, since such averages reflect an additive effect in a positive direction which eventually leads to highly significant

differences, even though differences from year to year are small and insignificant.

This investigation also gives interesting data on the combining ability of the crosses investigated and performance in subsequent generations. Investigations with other crops, such as wheat, Harrington (**23**, **24**), and barley, Immer (**31**), indicate that combining ability in early crosses, F_1 and F_2, may be indicative of the performance of later generations. The results of this study show that none of the crosses resulted in a consistently high producing F_2; in fact, significance over the most productive parent in the F_2 was recorded for only two crosses, and both of these occurred in **1943**, the year of low productivity. The data seem to substantiate those of other workers in *Gossypium* in that they indicate that productive F_1's do not necessarily give high average production in subsequent generations.

In the selection of the three strains used in the investigation, the authors stated, " The Coker 100 and Stoneville lines are related. . . . Deltapine 11A is of hybrid origin and not known to be related to the Coker and Stoneville varieties ". The pedigree of the hybrids studied shows that five were Stoneville × Coker, the other being Stoneville × Deltapine. It is evident from the data that the Stoneville × Deltapine hybrid population is distinct from the other crosses. It is interesting to note that the F_1 of this cross was the only one that gave significant increases over the more productive parent each year. This evidence is in accord with that reported for other species; namely, that combining ability is more pronounced in hybrids of relatively unrelated strains.

The work of Kime and Tilley has contributed materially to knowledge on three important points regarding heterosis in cotton: (*a*) significant heterosis in F_1 generations from certain intraspecific crosses has been demonstrated; (*b*) combining ability, as evidenced by increased production, was not expressed in the F_2 generations of productive F_1's; (*c*) greater increases in F_1 heterosis may be expected in crosses involving relatively unrelated lines.

Simpson (**58**) conducted an investigation to determine the extent of heterosis exhibited in progeny resulting from seed produced in an area in which natural cross-pollination by bees and other insects approximated **50** percent. Seed from seven varieties were obtained from two sources: (*a*) commercial seed, produced in isolated fields and designated as " inbred "; and (*b*) open-pollinated seed from **1946** variety test conducted at Knoxville, Tennessee, which consisted of **25** varieties in replicated, randomized blocks, and designated as " crossed ". The crossed seed were obtained from known female plants, the pollen parents having been a mixture of the **25** varieties in the test. Under the conditions of the experiment approximately **50** percent of the crossed seed were self-fertilized, the remainder being crossed either with the other **24** varieties or with sister plants of the same variety.

Heterosis was noted in seedling and young plant growth, and it was stated, " On several occasions, visitors unfamiliar with the layout were asked to choose the more vigorous and productive of the paired rows. The crossed rows were chosen in approximately **70** percent of the cases ".

Data were recorded for yield, size of boll, percentage of lint, seed index, lint index, lint length (UHM), lint strength (Pressley) and lint fineness. No significant differences were reported between crossed and inbred seed for percentage of lint, lint length, lint strength, fineness or uniformity. Relative to boll size it was reported, " For the whole experiment, the crossed bolls were significantly larger than the inbred bolls. The increase in boll size was confined exclu-

sively to small-boll varieties. The data indicate partial dominance for large bolls. There is no indication of heterotic effect on boll size ". Lint indices were consistently higher for crossed than for inbred stocks of all varieties, but significant differences were recorded in only three cases. Seed index was significant in only two instances, but the entire experiment showed a small gain in favor of the crossed seed.

Yield of seed cotton was the character in which the greatest heterotic effect was noted. In discussing this character, Simpson reported, " The yield of the crossed seed exceeded that of the inbred in each of the seven varieties, the range for these excess yields being from 5.7 to 44.2 percent. Three of the individual differences were more and four were less than required for significance. In field experiments it is extremely difficult to have conditions sufficiently uniform to obtain a low experimental error. Differences of less than 10 percent in yield are usually statistically non-significant in cotton experiments of this size. Differences of 5 percent or less, however, are of agronomic importance and indicate definite trends when such differences are consistent ". The seven crossed seed sources produced an average of 15.4 percent over the inbreds. It is believed that the data presented have added valuable information to one phase of the problem of heterosis in cotton, *i.e.*, that crossed seed produced in certain areas with a high percentage of natural crossing may account for significant increases in yield over stocks produced from inbred seed of the same parental varieties. A critical evaluation of the data, however, necessitates re-examination of the figure of 15.4 percent average increase, when it is noted that greatest increases are evidenced in varieties which, in general, were the lowest producers in the 1946 variety test from which seed were obtained. The 1946 mean yield for the 25 varieties was 1354 pounds of seed cotton per acre, with Stoneville 20 producing 294 pounds less than the test average. In comparing the yields attributable to natural crossing, Stoneville 20 gave an increase of 44.2 percent over inbred seed. The other extreme in yield of the 1946 test, Cobal × Bal, with a production of 189 pounds over test mean, gave an increase of only 6.4 percent for crossed over inbred seed. This same general trend is noted for other varieties tested. On the whole the high percentage increases for crossed over inbred seed sources were recorded for varieties with the lowest base production. It is also of interest to note that in the case of Stoneville 20, with an increase of 44.2 percent, the crossed seed still produced less than the crossed seed of four of the varieties tested, and was not significantly greater than two others. Of still greater importance may be the fact that the crossed seed of Stoneville 20 produced less than two inbred sources of more productive varieties.

Based on the amount of heterosis exhibited in the yield of the crossed seed, Simpson has suggested two possible methods of hybrid seed production. One method was the production of a limited amount of F_1 seed, by hand pollination, between lines in which significant heterosis has been found in test crosses. These F_1 seed would then be increased in multiplication fields in areas with high natural crossing, commercial seed being produced in second and third generations by natural cross pollination. The second method suggested was that of planting a mechanical mixture of two or more inbred strains of proven combining ability and propagating the bulked seed stock for several generations. Commenting on the latter method, Simpson stated, " The percentage of hybrids and the effective heterosis would be dependent on the amount of natural crossing. Further multiplication of seed developed

in this way could be continued through several generations, with heterosis being partially maintained by the crossing and back-crossing that would occur in a mixed population ". In support of the proposed methods of hybrid seed production, Simpson presented the following points: " The superior performance of the early generations of hybrids between inbred strains is a common observation among cotton breeders. This and the extent of hybridization by natural crossing indicated in our results suggest that hybrid vigor in the advanced generations may be utilized in cotton improvement . . . the regression of the yield of a hybrid between homozygous lines toward the average of the parent lines would be ½, ¾, ⅞, etc., of the original excess, only if the successive generations of the hybrid were propagated by self-fertilization. Under completely random mating, as approximated in corn, there is no further decrease below the F_2 yield. With the partial selfing and partial inbreeding as would occur in open-pollinated cotton, there would be some intermediate result. While that intermediate result can not be predicted, the inter-crossing indicated by the results here suggest that an appreciable degree of heterosis might well be retained through the few generations needed to increase a small amount of hand-pollinated F_1 seed to commercial quantities ".

Apparently the methods of seed increase suggested by Simpson are based on the assumption that the heterosis exhibited in the F_1 progeny will persist in yield in F_2 and subsequent generations at a higher level than that of the yield of the parental strains. The limited data available on the behavior of F_2 and later generations from other sources do not indicate that such segregating populations will continue to show yield increases. In view of the meager experimental evidence presented to date, plans for seed production suggested by Simpson might profitably be subjected to further experimental investigation before attempts are made to employ them on an extensive commercial scale.

Stephens (63) has given theoretical consideration to the use of advanced generation seed and suggested that with 50 percent outcrossing and assuming that vigor is a function of heterozygosity, vigor would fall to about 33 percent in four generations and thereafter remain stable. According to Stephens, " This would only be true if we make certain further assumptions. First, the calculations which have been presented are based on the assumption that all gametes are equally viable. Evidence is steadily accumulating that this assumption is invalid for interspecific hybrids like Upland/Sea Island crosses. As yet, however, we have no reason to suspect that this would be an important factor in intervarietal hybrids so it need not be considered further. Second, the calculations assume that gene action is additive. This is certainly not true for any specific gene pair. Cases are known where the effect of two genes acting jointly have less than double the effect of each gene acting singly (interaction). On the other hand there is ample evidence from recent work in physiological genetics that genes frequently have no effect at all unless other genes are present simultaneously (complementary action). Since complementary action and interaction would work in opposite directions they would tend to neutralize each other. In making use of the additive scheme which has been outlined we must therefore assume that these two effects cancel each other. It is a simple assumption which may or may not be justified. The acid test, of course, is whether it fits experimental data. In cotton there appears to be little information on the actual amount of hybrid vigor retained, and to estimate it satis-

factorily it is necessary to compare the average performance of successive generations when grown together in a properly replicated experiment ". Stephens continues, " Assuming on these very limited grounds that the theory is valid, it is clear that the amount of hybrid vigor retained with 50 percent outcrossing will only be of commercial importance if the initial amount in the F_1 is sufficiently high. For instance, in Kime and Tilley's material five intervarietal F_1 hybrids grown over a three-year period gave an average increase over the mean yields of their parents of 18.8 percent. Theoretically only 33 percent of this increase or 6 percent should be retained in subsequent generations under a system of 50 per cent outcrossing. It seems doubtful if an attempt to exploit vigor of this order would be commercially advantageous unless one could be very sure that the level of outcrossing could be maintained. The point to be remembered is that 33 percent heterozygosity represents a *maximum*—any seasonal drop in degree of outcrossing could reduce this figure appreciably, though, of course, it could be built up to 33 percent again in subsequent generations if the level of outcrossing were restored ".

Simpson (59) conducted a test to determine the extent of heterosis resulting from natural crossing at various " seed source " locations over the Cotton Belt. Selected varieties were obtained from variety tests, spinning tests, etc., at various locations in New Mexico, Texas, Mississippi, Alabama, Georgia, Tennessee, California and North Carolina. There were a total of 132 comparisons made between " crossed " and " breeders " seed (crossed seed being the designation of seed from variety tests which had been exposed to outcrossing with other varieties, while breeders' seed refers to uncontaminated stocks obtained from breeders or seedsmen). In these 132 comparisons, crossed seed gave higher yields in 106 paired-row plots, 20 plots were equal in yield, and in six cases the crossed seed produced less than the breeders seed. A number of different varieties were included, and some varietal differences were noted; however, the differences were not large enough to be significant. In an analysis of seed from different regions of the Cotton Belt, the amount of natural crossing was assumed to be reflected in the yield of crossed seed from the different localities. Differences due to locations were noted, with seed from certain localities being significantly higher than those from other localities. Crossed seed from only one location, Greenville, Texas, failed to yield significantly more than breeders' seed. In conclusion it was stated, " These data leave little doubt that effective natural crossing occurs rather generally over the Cotton Belt, beyond this, comparisons between localities are unwarranted. . . . Evidence of larger yields from the crossed seed from widely scattered locations indicates that this is no local problem. The data reported here are but a crude beginning of the information that must be acquired if we are to explore adequately the practical possibilities of hybrid cotton ". Though the data are impressive, it is difficult to reconcile the increases in yield obtained with the relatively low percentages of natural cross pollination that is known to occur at a number of the " seed source " locations. It is not improbable that certain physiological factors and differential interactions of physiological responses with the genotypes at the various " seed source " locations played a part in the differences obtained at Knoxville, Tennessee, a location somewhat beyond the northern limits of the presently accepted Cotton Belt. One is inclined to withhold unqualified acceptance of the interpretation until such time as progenies of both self- and open-pollinated material from a number of

" seed source " locations are compared at Knoxville or some other designated point.

Turner (70) reported data on 492 different hybrids made in 1946 and grown in 1947 field trials. Of the 492 combinations, 14 displayed enough vigor to warrant additional study. Yield increases of 18 to 44 percent over the best locally adapted commercial variety were obtained in these 14 selected combinations. The use of the best commercial variety or varieties as the standard of comparison in testing the performance of hybrids is the logical approach to the practical evaluation of hybrid cotton. These results, reported by Turner, represent the first such comparison made with a large number of hybrid combinations.

Kime (38) conducted tests during 1947, 1948 and 1949 to determine combining ability of ten inbred lines. All of the 45 possible hybrid combinations were made and tests each year included the hybrids, the ten parent lines and one commercial variety. General and specific combining ability were calculated for yield of lint and for the three components of yield—bolls per plot, seed per boll and lint per seed (lint index). It was reported that the value of the hybrids on the basis of combining ability varies according to the yield component under consideration. No individual parent line was found to be outstanding for all three yield components in either specific or general combining ability. No combination of parental lines, which were poor for any particular character, produced hybrids outstanding for the same character when compared to the best inbred lines. No important discrepancies were noted between general and specific combining ability.

Intravarietal Crosses. The expression of heterosis in intravarietal crosses of *Gossypium* has been investigated in only a few instances, and the discussion of this phase may be of more academic interest than practical application. Heterosis in intravarietal crosses may be determined in two ways: (*a*) the resultant loss of vigor upon selfing of open-pollinated varieties in which the differential in vigor of vegetative characters and yield, found between the selfed and open-pollinated strains of the same variety, is attributed to heterosis from intravarietal crossing; and (*b*) the crossing of inbreds of the same line or family and measuring heterotic responses.

One of the first reported studies on this subject was by Kottur (42) in which a strain of *Gossypium herbaceum* was selfed for 12 years and tested for height of plant, total length of limbs, sterility of anthers, shedding of flowers, number of bolls per plant, yield of seed cotton per plant, ginning percentage, staple length and seed weight. No deterioration was noted in any of these characters; however, it was stated, " Sometimes a variety yields more than its pure line which is selected for yield. The cause of this is found not in the deterioration of the selection due to selfing, but in hybrid vigor of the F_1 plants appearing in the open pollinated seed of the variety ". Hutchinson (26), in discussing the terms " deterioration due to selfing " and " hybrid vigor of the F_1 ", as used by Kottur, made the following statement which is of interest in an analysis of F_1 vigor in intravarietal crosses: " Surely, on whatever theory we interpret hybrid vigor both phenomena are manifestations of it. To attribute to hybrid vigor the greater production of a variety over its pure line selected for yield is therefore illogical if it is maintained that there is no reduction in vigor on selfing ".

Heterosis in intravarietal hybrids of *G. hirsutum* was reported by Brown (10) who studied crosses of inbred strains of the Express variety in 1921 and reported as follows: " A row of F_1 plants from a cross of two inbred strains

was planted between rows of the two parent strains and handled the same in every particular. The average height of the plants of the F_1 strain was 98.5 cm. The average height of the parent strains was 88.0 cm. The F_1 strain produced 36.6 percent more flowers than the average of the parents, and 25 percent more seed cotton ".

Brown, Cotton and Neal (13) reported an experiment begun in 1928 to determine the effects of inbreeding on vigor and production in cotton. They found that the crosses within varieties made an average of 16.1 percent more cotton than the selfed strains of the same variety during the first year of the test; the next three years little difference was noted, but the crossed strains were more productive every year but one. For the next four years the crossed strains led in production consistently, the gain in 1935 being 18.6 percent. An increase in boll size and rate of blooming was also noted in crossed strains. The writers concluded, " It now seems fairly evident, however, that the inbreeding does reduce production to a limited extent, and it also seems to reduce boll size, rate of blooming and vegetative growth early in season. . . . The effect of inbreeding on lint length, on lint percentage, and some other characters was also studied but certain effects could not be determined ".

Brown (12), in a later and more complete report of the same investigation, presented the plan of the experiment and the results of ten years of inbreeding. The experimental design consisted of selecting 50 typical plants from eight commercial varieties in 1928. Two bolls on each plant were selfed; two more on each plant were crossed at random with pollen from the other plants. The 100 selfed bolls were massed and seed for planting chosen in such a manner as to avoid selection, the 50 crossed bolls being treated in the same manner. Crossed and selfed lines were planted in alternate rows. Selfed seed for each additional year were secured from the selfed rows of the previous year and crossed bolls produced in the row from crossed seed, using the procedure given above. This was continued for ten years and the following results were reported: " Although there were some inconsistencies in individual cases, the averages for the several varieties for the whole experiment indicated rather definite trends. The crossed strains had greater vegetative growth, did more blooming, had larger bolls, opened bolls earlier, and had greater production of seed cotton, indicating greater vigor and fruitfulness. The differences between strains was not great, but it was great enough and regular enough to mean something. . . . Inbreeding eight varieties of Upland cotton at Baton Rouge, Louisiana, for a period of 10 years resulted in an average reduction of 9.3 percent in production of seed cotton, a 1.6 percent reduction in blooming rate and a 9.3 percent reduction in boll size ".

O'Kelly (50) reports an experiment conducted over a period of several years in which five varieties were tested to determine what changes occur within a variety when mixing with other varieties is prevented. He reported that the proportion of bare seed increased as the variety was reproduced year after year, with the increase being slow at first and more rapid in later years. A decrease in lint percentage was observed, which was attributed to the increase in numbers of bare seed. Changes in seed cotton yields and staple length were too variable to be properly evaluated.

Humphrey (25) reported that inbreeding cotton varieties brings rapid segregation into many types which become relatively uniform after two or three generations, with little more uniformity after seven years of inbreeding as compared to two years. Most commercial varieties were found to be very non-

uniform, particularly for fiber characters. In discussing the work of Humphrey, Brown (12) has this to say, " No comparison is made by Humphrey between the lint length and lint percentage of the inbred strains and their open-pollinated parents. The figures given in his tables, however, show a shorter staple length and lower lint percentage as the inbreeding progressed ".

Brown (12) also reports some unpublished work of Dr. J. W. Neely, Stoneville, Mississippi, in which eight inbred strains of eight Upland varieties were grown in comparison with their open-pollinated parents. " In every instance ", according to Brown, " the height of the open-pollinated plants was greater than that of the selfed strains, the average in their favor being 6 inches. Two of the selfed strains averaged 10 inches lower than the open-pollinated strain of the same variety ".

Krasovskii (43) reported that open-pollinated plants flowered two-three days earlier, ripened sooner and had more bolls per plant and seed per boll than varieties selfed for a long period of time.

Ter-Avanesjan (68) made comparisons between progenies from open-pollinated lines and intravarietal crosses of the same line. It was found that the plants from the intravarietal crosses were more vigorous and uniform in development. Different varieties were reported to respond differently to intravarietal crossing.

Tsinda (69) reported that F_1 crosses within varieties of *Gossypium barbadense* made in 1937 showed greater germination, greater increases in seed cotton, higher lint quality and picked earlier; no differences were noted in boll size, lint length or percent lint. Similar results were obtained when the experiment was repeated in 1938 with three varieties of *Gossypium hirsutum*. Tsinda also reported that significant differences still existed in the F_2 and that greater response was obtained when crosses were made between lines of the same variety coming from different areas. In a critical analysis of this work a question is immediately presented with regard to the statement, " greater response was obtained when crosses were made between lines of the same variety from different areas ". In the latter case it is highly probable that crosses between " biotypes " of the same variety which differed in genetic constitution as a result of either natural or artificial selection, were involved rather than extractions from genetically pure original stock. In such an event the crosses should be classified as intervarietal rather than intravarietal.

Kearney (35) reported that inbreeding in Pima, *Gossypium barbadense*, for a seven-year period did not result in any reduction in growth and production. Brown (12), commenting on this work, suggests that " a possible explanation of this may be found in the fact that plant selections were made each year and propagation was from these select productive plants ". Since the Pima variety sprang from a single exceptional plant (Kearney 34) and was propagated continuously by inbreeding without measurable loss in vigor, it seems reasonable to conclude that the original progenator was homozygous for the genes which conditioned the major morphological and agronomic characters. Under such circumstances it is unnecessary to assume reselection of productive plants to explain the findings. Harland (22) calls attention to the fact that Montserrat, a variety of Sea Island cotton, was also the progeny of a single plant of " lucky find ". As in the case of Pima, the variety showed no loss in vigor after many years of inbreeding. Both of these varieties were members of the *barbadense* species, and it is interesting to speculate as to the reason why

no such striking examples have been reported in the American Upland or *hirsutum* group. In this connection it should be mentioned that both of these varieties have been replaced by more productive types which have been bred by methods other than plant-to-row selection or strict inbreeding.

Production of Hybrid Seed

Considerations of methods and procedures for the production of hybrid cottonseed in commercial quantities fall into three general categories: (*a*) hand pollination; (*b*) natural cross pollination; and (*c*) use of male-sterile or semi-male-sterile stocks. The review of hybrid planting seed production to follow will be confined to a consideration of F_1 hybrids, there being, at present, little experimental evidence of the practicability of advanced generation stocks.

Hand Pollination. Controlled emasculation and pollination by hand is obviously the most certain method of obtaining F_1 hybrid seed. However, practical difficulties are encountered in the production of F_1 hybrids by this method. The cotton flower is perfect, and, while emasculation and pollination by hand are by no means difficult, the operations are time-consuming. Furthermore, only a few, 25–40, seed are set in each boll or fruit. The cost of labor involved in the production of seed in commercial quantities by this method would be practically prohibitive. The method may prove to be of value in areas in which there is an abundance of cheap hand labor or where cotton is propagated as a perennial, thereby eliminating the necessity of producing an annual seed supply. Since neither of these conditions exists in the Cotton Belt of the United States, it is unlikely that hybrid seed production by hand pollination will be practiced here on an extensive scale.

Natural Cross Pollination. Simpson (58) has suggested two methods of seed production utilizing natural cross pollination; the merits of these methods have been discussed elsewhere in this paper. It is readily apparent that seed production by natural cross pollination will be limited to areas in which natural crossing is relatively high, and such areas in the Cotton Belt are not well defined at present. Simpson (59) conducted an experiment at Knoxville, Tennessee, with the specific objective of determining maximum natural crossing, and reported from 43.8 to 58.7 percent. No reduction in the amount of natural crossing resulted in dusting with benzene-hexachloride.

Reports on the amount of natural cross pollination in cotton, dating almost from the turn of the century to the present, may be found in the literature. Data from such reports have been summarized in Table II. Percentages of natural crossing in areas outside United States are given in Table III. Such data, taken sporadically and over a long period of years, give some idea of the wide differences in amounts of natural cross pollination to be expected, but they furnish little in the way of uniform information from which to select definite areas where natural crossing is sufficiently high to warrant consideration for commercial hybrid seed production. Regional natural crossing studies now being conducted in all Cotton Belt States should be very valuable additions to the knowledge regarding this phenomenon. The data when summarized and published should also be of value in determining the feasibility of this method of hybrid seed production and aid in the definition of areas in which relatively high amounts of natural crossing may be expected.

Consideration of natural crossing as a possible method of hybrid seed production necessitates the accumulation of information relative to two other prob-

lems, namely, what insects are most effective in cross pollination and are there differential varietal responses to natural crossing in Upland cotton?

Cotton breeders are of the opinion that the bumble bee, *Bombus* spp., is one of the most important insects in the cross pollination of cotton. Meade (46) reported in 1918 that the honey bee was an effective pollinator and suggested that beekeeping might increase cotton yields. Information on the role of insects in pollination of cotton is, like natural crossing data, for the most part rather fragmentary. Basic entomological investigations are needed to develop further information on the natural crossing in cotton.

Varietal responses to natural crossing have not been adequately studied. Preliminary investigations by Turner (71) and investigations currently being conducted by the senior author indicate that varietal interactions may be of considerable importance. Turner reported the results of three years with three inbred strains. These strains gave three-year means of 30.4, 20.9 and 19.8 percent natural crossing when planted in rows adjacent to red leaf cotton. The yearly averages of all strains were 23.0, 28.2 and 19.8 percent, respectively, for 1947, 1948 and 1949. Turner also reported that one variety, Florida Greenseed, produced 12.7 percent cross pollinated seed in the same test with an Acala strain in which 30.4 precent crossed seed was obtained. Tests conducted at Athens, Georgia, in 1948 by the senior author indicated varietal interaction to natural cross pollination in which nine commercial varieties were

TABLE II

PERCENTAGES OF NATURAL CROSSING IN COTTON REPORTED IN THE COTTON BELT OF THE UNITED STATES

Location	Investigators	Experimental design	Percent natural crossing	
			Maximum	Minimum
Fayetteville, Arkansas	Ware (74)	Alternate rows	40.90*	
Scott, Arkansas	Ware (74)	Alternate rows	1.00*	
College Station, Texas	Richmond, Harper & Beasley (54)	Alternate rows	9.00*	
College Station, Texas	Stroman and Mahoney (66)	Adjacent plants	3.28	1.76
Waco, Texas	Shoemaker (57)	Excess of male	10.90*	
Sacaton, Arizona	Kearney (35)	Alternate rows	11.00	5.00
Sacaton, Arizona	Kearney (35)	90 percent +	34.60	14.0
South Carolina	Webber (78)	Alternate rows	10.00	5.00
North Georgia	Allard (3)	Alternate rows	20.00*	
North Georgia	McLendon (45)	Alternate rows	2.00*	
South Georgia	Turner (71)	Alternate rows	34.00	11.00
South Georgia	Turner (71)	90 percent	33.50	25.80
Alabama	Turner (71) (quoting A. L. Smith)	90 percent +	42.90	40.00
Knoxville, Tennessee	Pope, Simpson & Duncan (51)	Alternate rows	27.20*	
Knoxville, Tennessee	Simpson (59)	90 percent	53.00	44.20
Mississippi	Brown (10)	90 percent +	81.00	57.00
Mississippi	Ricks and Brown (56)	Alternate rows	11.10	4.90
Mississippi	Brown (10)	Adjacent plants	19.00*	

* Average figures.

planted, using a common red leaf variety in alternate rows. These results indicated differences ranging from 1.75 to 6.01 percent.

Since 100 percent natural crossing is never attained, one of the practical problems of commercial hybrid seed production is how to recognize and remove the homozygotes from the seed-source planting in order that only F_1 plants will remain. The most practical approach would seem to be the use of parental stocks with marker genes which are easily distinguishable in the seedling stage. This would require a simply inherited, incompletely dominant character which would allow the heterozygotes to be identified in the first hybrid generation, or a recessive gene in the female parent stock which also would permit identification of F_1 hybrids in the progeny grown from it; the homozygotes could be eliminated during the ordinary practices of thinning and weeding. A character which appears most ideal in this respect is red plant body or red foliage. In the production of hybrid seed, using this marker, alternate rows of parental lines, one red and the other green, could be planted, the green leaf parent seed being harvested for planting seed stocks. When such stocks are planted the following year, all green plants will be removed, leaving only the dilute red or hybrid seedlings. This method would be more satisfactory than using both red and green leaf parents for planting purposes, since detection of the heterozygotes in a population composed of green leaf seedlings would be easier than detection of the F_1 plants in a population containing the red leaf parent. The red leaf character is manifest in the heterozygote immediately after germination (14). A satisfactory stand of F_1 plants could be assured by increasing the amount of seed planted per acre in such a way as to compensate for the estimated percentage of homozygotes in the seed stock. There is some evidence that the presence of the anthocyanin which causes the red plant color has a deleterious effect on yield. This point is not well substantiated by experimental evidence, and subsequent investigations may remove this objection to the use of the red plant marker character.

TABLE III

PERCENTAGES OF NATURAL CROSSING IN COTTON REPORTED IN COTTON PRODUCING AREAS OUTSIDE THE COTTON BELT OF THE UNITED STATES

Location	Investigators	Experimental design	Percent natural crossing	
			Maximum	Minimum
India	Kottur (41)	Alternate rows	6.00	
India	Afzal & Khan (2)	Alternate rows	3.45 2.00*	1.41
India	Afzal & Khan (2)	Adjacent plants	2.28 2.00*	1.91
China	Yu & Hsieh (79)	Alternate rows	7.79*	
Russia	Anonymous (1)	Alternate rows	9.00	4.00
Egypt	Balls (7)	Alternate rows	15.00	5.00
Egypt	Balls (9)	Alternate rows	35.00	5.00
India	Gammie (18)	....	none	....

* Average figures.

Another simply inherited character in cotton, which could be used in much the same manner as suggested for the red plant gene, is virescent yellow foliage. The planting of parental strains would be in alternate rows as described above, planting seed being saved from the virescent or recessive parent. By planting the seed of the virescent parent and removing all virescent seedlings, a hybrid stand of green foliage plants could be obtained.

The possibility of using two parent strains with complementary recessive characters is now being investigated at several locations. In such a scheme, planting seed could be obtained from both parents and thereby increased efficiency in seed production. In such a method of production one line might carry the virescent yellow character and the other parental strain would have another recessive marker, perhaps crinkle. The allele of both genes gives normal plants, and in the thinning operation on the progeny of the parental stocks, all virescent and crinkle plants would be removed, leaving a stand of F_1 plants, all of which would be normal in appearance. Such a method of seed production appears to be quite promising.

Green (20) reviewed the possibility of using seedling markers for increasing the stand of hybrid plants in stocks subjected to natural cross pollination and emphasized the need for additional markers. He made these general observations, " In considering markers now available, certain requisites can be established by which they can be screened. In the first place, they must be easily distinguished so that hybrid plants could be easily identified in the field; and second, they must not have associated deleterious effects that would make them unsuitable as parent lines or that would make the resulting hybrid undesirable ". It was also pointed out that marker genes are not present in the most productive lines or those lines which would make good hybrid combinations. A program to transfer these characters to lines of proven performance and combining ability must be activated if suitable marked lines are to be developed.

In view of the fact that hybrid cotton seed production in the United States by natural cross pollination methods is dependent, almost entirely, on the activity of bees, it is difficult to visualize how the necessary environment for such crossing can be provided for the production of large quantities of seed. Furthermore, the apparent great variation in crossing percentages from year to year will result in a variable product, which is undesirable in this age of specialization when farmers are demanding standardized products. It seems safe to predict that natural cross pollination methods of producing hybrid seed, if used at all, will first be used for limited scale production of specialty cottons.

Male-Sterile and Semi-Male-Sterile Stocks. The use of male-sterile or semi-male-sterile lines in the production of hybrid cotton seed is theoretically the most efficient method proposed. The male-sterile method has been suggested for hybrid seed production in barley (67), sorghum (61, 62) and tomatoes (16, 55). Smith (60) has suggested a possible practical method of producing hybrid seed by using a type of male sterility in which parental lines are maintained in certain environmental conditions conducive to fertility and seed setting, but which exhibit male sterility in the environment of the hybrid seed production fields. The male-sterile lines, or mother plants, would be planted in alternate rows with male or pollinator plants. Hybrid seed would be produced on these stocks as the result of cross pollination by insects.

Sterile or partially sterile stocks have been found in cotton; however, none as

yet has been used in the production of hybrid seed. Stroman (65) reported a female-sterile type in *Gossypium barbadense*. Hutchinson and Gadkari (28) found plants in *G. arboreum* which exhibited heritable sterility on both male and female sides in approximately equal amounts. Vijayaraghavan et al. (72) observed female sterility in *G. herbaceum*. Additional examples of genetic sterility have been reported in cotton by Kummar (44) and Ramiah and Gadkari (53). Hutchinson (27) reported a semi-sterile character in *G. barbadense*. Turner (70) found a self-sterile plant in a variety of *G. hirsutum* in the breeding plots of the Georgia Coastal Plain Experiment Station. The nature of the sterility manifest in this plant has been investigated by several workers, including the authors. Sterility in this stock is apparently due to physiological and genetic interactions, but, as yet, the genetics of the character is undetermined. It may be stated, however, that the type of sterility exhibited does not appear to be adapted to a program of hybrid seed production.

Hybrid seed production, utilizing male-sterile lines, even though theoretically possible, presents a major problem in the isolation and maintenance of the sterile lines. Breeders throughout the Cotton Belt have been asked to survey their material continually for suitable male-sterile types. One such plant was found in a field of cotton near Lubbock, Texas, by Mr. Don L. Jones, Superintendent, Lubbock Substation, Texas Agricultural Experiment Station. The nature of this sterility is now being investigated by the authors.

Green (20) has suggested the use of another character in which male-sterile-like characters are approximated, this character being the delayed dehiscence of pollen. According to Green, " Time of pollen dehiscence might be important in increasing natural crossing. Under Mississippi Delta conditions, the anthers of Acala 22 usually dehisce later in the day than do other varieties. Such a character in a ' female ' parent would tend to increase effectiveness of foreign pollen ".

Another variation of the male-sterile idea is the behavior of pollen tube growth in certain lines of cotton as reported by Harland (21). It was suggested that it may be possible to breed a cotton immune from natural crossing by selection of lines in which pollen tubes grow so rapidly in styles of the same flower that no foreign pollen can effect fertilization. If Harland's hypothesis that lines with fast growing pollen tubes could be selected and that foreign pollen could not effect fertilization is accepted, it then seems possible that the other extreme, or lines in which self pollen tube grows so slowly that foreign pollen would effect fertilization, could also be isolated. Such lines, even though not being truly designated as male-sterile, would produce the same desired end result. They might more appropriately be designated as self-incompatible.

It is believed that sufficient information has been reported to warrant the suggestion that seed production methods using male-sterile lines offer real possibilities in the development of hybrid cottons. However, it must be reiterated that such methods are not to be expected to be perfected in the near future and will be dependent upon the accumulation of basic and fundamental information on the sterility phenomenon in cotton.

Summary and Conclusions

Reported data on the general problem of heterosis in the genus *Gossypium* have been presented and discussed.

Evidences of significant increases in most plant characters and yield resulting from heterosis have been reported in

interspecific, intervarietal and intravarietal crosses. Such increases have been reported in commercial varieties of the four species *Gossypium arboreum, G. barbadense, G. herbaceum* and *G. hirsutum.*

On the basis of present data, maximum effect of heterosis is obtained in the F_1 generation, and few investigations indicate that subsequent generations may be expected to give significant increases, particularly in yield.

Three methods of hybrid seed production, hand pollination, natural cross pollination, and the use of male-sterile or semi-male-sterile stocks, are discussed.

The future of commercial utilization of heterosis in cotton production is believed to be dependent upon basic investigations of the numerous phases of the general problem.

Large scale commercial utilization of natural crossing to produce hybrid cotton seed is not to be expected in the immediate future.

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Utilization Abstracts

Pandanus Oil. *Pandanus odoratissimus*, the fragrant-flowered screw pine, is the only aromatic member of the family and is found as a shrub in India, Arabia, Persia, Burma, Andaman Islands and around Singapore. The leaves surrounding the blossoms are also aromatic, and both are sold together in local markets for perfumery purposes. The blossoms, known as "kewda flowers", are used in India mainly for the manufacture of kewda water and kewda attar, and the latter, *i.e.*, flowers distilled over sandalwood oil or refined liquid paraffin, is so popular in the country that it has the largest sale of all attars. (D. H. Dhingra et al., *Perf. & Ess. Oil Rec. 42: 114. 1951*).

Central American Edible Plants. In 1946 the nutritional biochemistry laboratories of the Massachusetts Institute of Technology, supported by a grant from the United Fruit Company, undertook to analyze all the edible flora of Central America, "plants that are eaten infrequently as well as those that are popular in the diets of the local population". While other components of these foods were also considered, special attention was given to their content of calcium, iron, carotene, thiamine, riboflavin, niacin and ascorbic acid. The study has involved nearly 12,000 determinations on more than 200 kinds of plants, and eight papers have been published, presenting the results, in addition to a ninth one briefly summarizing the entire project. All these articles contain not only technical data but also common Spanish and English names, scientific names and notes on the native uses of the many kinds of plant food considered. (Hazel E. Munsell et al., *Food Research 14: 144–164. 1949; 15: 16–33, 34–52, 263–296, 355–365, 379–404, 421–438, 439–453. 1950; Jour. Home Econ. 42: 629–631. 1950*).